Influence of Display Transparency on Background Awareness and Task Performance

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Figure 1. We conducted an experiment comparing a transparent display (*left*) with typical display configurations such as a conventional display at an angle of 30° (*center*), and a horizontal display (*right*) in a dual-task scenario (square-click as primary task, background observation as secondary task). Results show constant primary task performance for all configurations, but an increase in background awareness (i. e. stimuli detection rate) for the transparent (83%) and horizontal (70%) display.

ABSTRACT
It has been argued that transparent displays are beneficial for certain tasks by allowing users to simultaneously see on-screen content as well as the environment behind the display. However, it is yet unclear how much in background awareness users gain and if performance suffers for tasks performed on the transparent display, since users are no longer shielded from distractions. Therefore, we investigate the influence of display transparency on task performance and background awareness in a dual-task scenario. We conducted an experiment comparing transparent displays with conventional displays in different horizontal and vertical configurations. Participants performed an attention-demanding primary task on the display while simultaneously observing the background for target stimuli. Our results show that transparent and horizontal displays increase the ability of participants to observe the background while keeping primary task performance constant.

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INTRODUCTION
Various researchers proposed transparent displays as a medium for collaboration and to increase consequential awareness and situation awareness (e. g. [10, 20, 21, 22]). They offer potential benefits in situations where users want to simultaneously observe screen content and the environment behind the display, or when attention is frequently switched between the two.

With conventional (opaque) displays (e. g. computer screens), usually positioned in front of a user, important events such as a person approaching, a colleague beginning to be available for communication, or a situation change in a command-and-control room can remain unnoticed since the displays block the view on the environment.

In order to overcome challenges of conventional displays, prior work has used horizontal displays (i. e. vertically tilted conventional displays) such as tabletop displays to allow users to perform individual or collaborative tasks while simultaneously observing the environment for important events. Additionally, in situations where the locations of important events are known, users typically position their display in a way that the environment is not obstructed.

It is yet unclear how transparent displays compare to conventional and horizontal displays when users perform a primary task on their display and simultaneously try to be aware of events happening in the background (i. e. secondary task). Transparent displays have the benefit that users' primary task as well as the background are within the same visual area. In contrast, conventional opaque displays have to be moved aside to unblock the view and see the background. Horizontal displays intrinsically increase the visual angle between primary task and background since they are vertically tilted. However, in contrast to conventional displays, transparent displays no longer shield users from motion or other distractions occurring in the background.

Until now, most research focused on the benefits of transparent displays e.g., for communication and collaboration (e.g., [10, 20]). However, the effects of background awareness and impact of distraction as well as the gain in background awareness have not yet been investigated and quantified. It is hence unclear how display transparency influences users' task performance, both in terms of objective measure (e.g., time and errors) as well as subjective measures.

In our work, we conduct an experiment to investigate if transparent displays are useful for dual-task scenarios, and how they compare to conventional opaque displays that are offset from the background in which events occur, as well as horizontal displays. We are concerned with situations where users perform a regular task on their main display while *simultaneously* observing the environment for specific events, for example in command-and-control rooms. Other observation scenarios include air traffic controllers performing regular tasks while reacting to events triggered by their colleagues, or security members in a stadium observing a large crowd while performing regular control tasks on a display.

We compare a transparent display with conventional displays at three different locations with respect to the background (directly in front of participants, at 30° and 60° beside participants), and a horizontal display. Participants performed an attention demanding primary task (square-click, cf. [31, 28]) and were instructed to react to specific stimuli in the background (letters). Background stimuli were displayed on a 100" projection 4 meters away from participants, which results in an observation area of 30° in participants' visual field (see Figure 1 and 6). Besides these target stimuli in the background, participants had to ignore other distractor-stimuli.

Our findings show that participants were able to focus on their primary task across all conditions, keeping their time and error rates constant. However, their ability to identify target stimuli was highly influenced by display configuration. For the conventional display positioned at 30° at the side, participants identified only around 55% of target stimuli, although the position was optimal in terms of visual angle (i. e. the visual field of interest was contiguous). Both the main display and the background were within their central to mid peripheral vision. Still, participants missed nearly half of the target stimuli. Background stimulus detection rates were best for the horizontal display (70%) and the transparent display (83%).

In the following, we present scenarios which we considered when designing our experiment, followed by background information regarding our choice of conditions in terms of display configuration. We argue that the positioning of displays and the resulting obstruction of visual field plays a key role for users' ability in the described dual-task scenario. Subsequently, we present our experiment, with quantitative and qualitative results. We conclude by discussing our results and giving implications and recommendations.

SCENARIOS

We designed the tasks used in our experiment with the following scenarios in mind.

1) A clerk at a train station performs organizational tasks on the display in front of her (see Figure 2). She sits behind an open counter, which allows her to talk to approaching passengers as well as observe the train station for specific events. Such events include people looking for guidance or other events which she can handle or report to colleagues. The display also allows her to see approaching people and talk to them while looking up information without blocking her view.

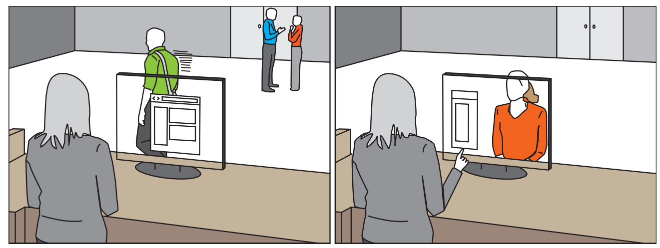

Figure 2. Scenario with a clerk performing tasks on her transparent display while observing the background (*left*) for important events such as a customer approaching (*right*).

2) A project manager supervises a team of designers and programmers. She performs organizational tasks individually but simultaneously observes the office for events such as approaching clients, or colleagues approaching a large shared whiteboard situated in front of the room at a distance of a few meters. The whiteboard is used to keep track of tasks, with post-it notes relating to specific tasks, based on the current iteration of the software the team is developing. Team members can approach the whiteboard and take post-it notes with them to perform tasks. She needs to loosely keep track of who performs which task and help colleagues choosing tasks.

3) A shuttle flight controller works in a large mission control center. Her duties include supervision of other personnel. She monitors her personal display to keep track of incoming data while keeping track of her colleagues and respond to unforeseen events. The large shared display in front of the room also includes statistics and real-time data. The room is busy with other personnel coming and going. Furthermore, she has to answer incoming requests from colleagues approaching her, for which she needs her computer.

In all these scenarios the high-priority task is conducted on a personal display, therefore it is the users' *primary task*. Simultaneously, users observe the background for different types of events. Since there is constant motion in the background (e. g. through visitors, moving colleagues, or interactive content on a large shared display), users have to process information and actively ignore stimuli and unimportant events.

Primary tasks like the ones described are typically performed with either vertical or horizontal displays. Clerks and office workers use conventional displays to perform their tasks and position them that they do not block the view on the environment they want to observe. Horizontal displays (e. g. tabletops) are common equipment in command-and-control rooms since they can be approached by multiple people and allow for seeing the environment. Furthermore, laptop computers provide the same benefits since they do not block the view on the environment when positioned on a table. We see them as tilted horizontal displays, also reflected in our experimental conditions.

Keeping these scenarios in mind, we designed the primary task to be attention demanding while the background stimuli are rather fast and constantly changing. Additionally, participants have to actively ignore stimuli and cannot simply respond to all events in the background, resembling the scenario of a busy environment.

RELATED WORK

In the following, we discuss related work from the research on transparent displays, dual-task scenarios, and display factors.

Transparent displays

One of the first to introduce the idea of using transparent displays for collaboration were Tang and Minnemann with their systems VideoDraw [36] and VideoWhiteboard [35]. This was later digitally enhanced and extended by Ishii et al. with Clearboard [14]. Hirakawa and Koise [11] extended the idea by combining it with camera tracking and AR components. While these systems focused mostly on remote collaboration, the idea of using transparent displays for co-located collaboration remained imminent.

Olwal et al. introduced FogScreen [26] and Consigalo [27], systems which are based on a two-sided projected fog display, and used them for multi-user face-to-face collaboration. Heo et al. [10] and Lee et al. [17] developed Transwall and Janus, respectively, two dual-sided see-through displays to foster collaboration, communication and awareness. Li et al. [20] proposed their FacingBoard-2 system, a dual-sided see-through system which was designed for co-located collaboration. Additionally, they showed that transparency is beneficial for collaborative situations [19]. Lindlbauer et al. [22] created Tracs, a transparency-controlled display that can selectively toggle between transparent and opaque state.

We contribute to research on transparent displays by investigating whether they are beneficial for dual-task scenarios and how they compare to conventional displays.

Dual-task performance and observability

Dual task scenarios have been investigated in the context of reading (e.g., [25]), pointing with task-relevant stimuli (e.g., [15]), and peripheral displays (e.g., [2, 24]). Probst et al. [28] and Hausen et al. [9], among others, investigated the idea of using separate input devices for peripheral interaction, which involves interactions that take place during or as interrupts of primary tasks. Bartram et al. [1] investigated the influence of motion on detection and distraction for on-screen notifications during a dual-task. Maglio and Campbell [24] investigated peripheral information displays, also in the context of performing dual-tasks. In contrast to our work, both Bartram et al., and Maglio and Campell focused on observability and notifications on a single display and how user reaction is influenced by different cues (e. g. motion, change in shape or color).

Reetz et al. [30] investigated the influence of gesture size on observability, more specifically on users' ability to observe others' actions (i. e. consequential awareness, cf. [8]). Our work is informed by their idea of different user configurations with respect to target stimuli (in their case gesture size, in our case display configuration) and their influence on task performance and consequential awareness. Furthermore, in the field of computer-supported cooperative work (CSCW), research focused on the impact and importance of consequential awareness (e. g. [8, 36]).

Our work contributes by providing insights into the influence of users' ability to observe the background with respect to typical and novel display configurations.

Display configuration

Inkpen et al. [13] explored the influence of different display factors on co-located collaboration. They report on a variety of factors influenced by the configuration, e. g. participants noted different ergonomic issues between vertical and horizontal displays. Ichino et al. [12] investigated the influence of display configuration in a museum context and found that tilted displays increased user experience (e. g. attracted attention and increased understanding of content). Forlines et al. [6] showed that both display configuration and group size influence the performance for visual search tasks. They tested single and multiple vertical displays as well as horizontal displays and found, among other things, that the choice of display influences reaction times. Rashid et al. [29] presented a survey of the influence of display factors on attention switching. They discussed user performance when using displays at different levels of depth as well as size.

Besides this work, a large body of work focuses on display size as influencing factors (e. g. [4, 23]). Swaminathan and Saton [33] provided a framing for various display configurations with displays spreading across a the visual field and across multiple levels of depths. They refer to displays which spread seamlessly across the visual field as *desktop-contiguous*, and to displays covering multiple visual areas (i. e. gaps between displays) as *non-contiguous*.

In our experiment, we adopt both types, desktop-contiguous and non-contiguous, as baselines for comparison with a transparent display.

Tan and Czerwinsky [34] investigate the influence of visual separation and physical discontinuities in a multi-task scenario (primary task and notifications). They focus on dual-display and display + projector setups, distributed on multiple depths. Their findings suggest a minor decrease in task performance when performing tasks on a display while reacting to notifications in the background. We extend their experiment for larger distances between display and projector (i. e. non-contiguous), as well as to horizontal and transparent displays.

In our work, we include the effects of display transparency as an important factor for dual-task scenarios. While having been proposed for a variety of use cases, it is yet unclear if users actually benefit from a transparent display or if potential benefits are outweighed by distraction from the background behind the display.

BACKGROUND

Traditional desktop computer setups feature one or multiple vertical displays, occluding a certain area of the background. As depicted in Figure 3, a single 22" display at a distance of 90 cm occludes approximately 30° of a user's visual field, roughly covering the central and near peripheral part. By increasing the number of displays or the display size, an area covering the mid peripheral visual field becomes occluded, limiting users' ability to observe events in the background.

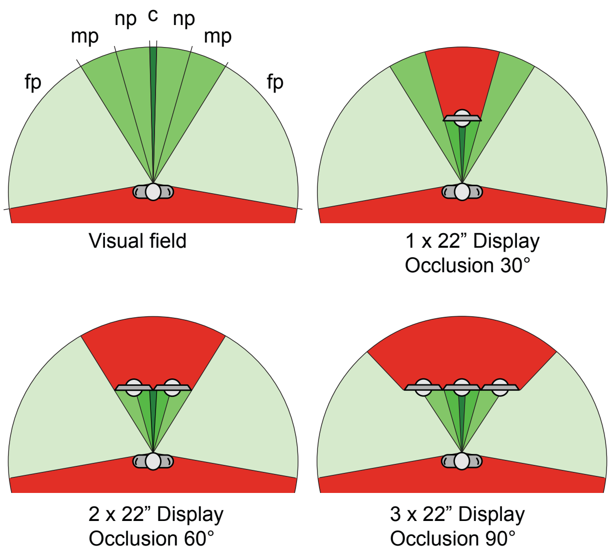

Figure 3. Occlusion in the visual field depends on display configuration. Red marks areas not visible to users. *Top left* illustrates properties of the human visual field with *c* (central) ranging from 0° to +/-1.5° , *np* (near peripheral) from +/-1.5° to +/-15° , *mp* (mid peripheral) from +/-15° to +/-30° and *fp* (far peripheral) from +/-30° to +/-100° .

When using conventional vertical displays, users have to configure (i.e. position and rotate) them in a way that they do not occlude important parts of the background. Prior work suggests that, when using multiple displays at different depth levels [29], having the displays edge-aligned results in no significant decrease in performance. We believe that users will exhibit the same behavior for observing events not only on a secondary display but also in the environment behind or beside displays. Dependent on the probability of important events in a certain area in the background, users will choose the position of their display accordingly, as depicted in Figure 4. Since the area behind the display is occluded (covering approx. 30° of users' visual field), the display has to be positioned beside the important area. In the best case, important events only occur in the area anticipated by users (Figure 4, green areas), i.e. right beside the display at a angular distance of within 30° to 60°. Events occurring outside this area potentially remain unnoticed since they lie outside users' mid and far peripheral visual field.

Dependent on the screen real estate needed to perform tasks, the area which users can observe simultaneously while performing primary tasks on their displays can be highly limited. As depicted in Figure 3, a three display configuration (covering approx. 90° visual field) leaves approximately 55° of

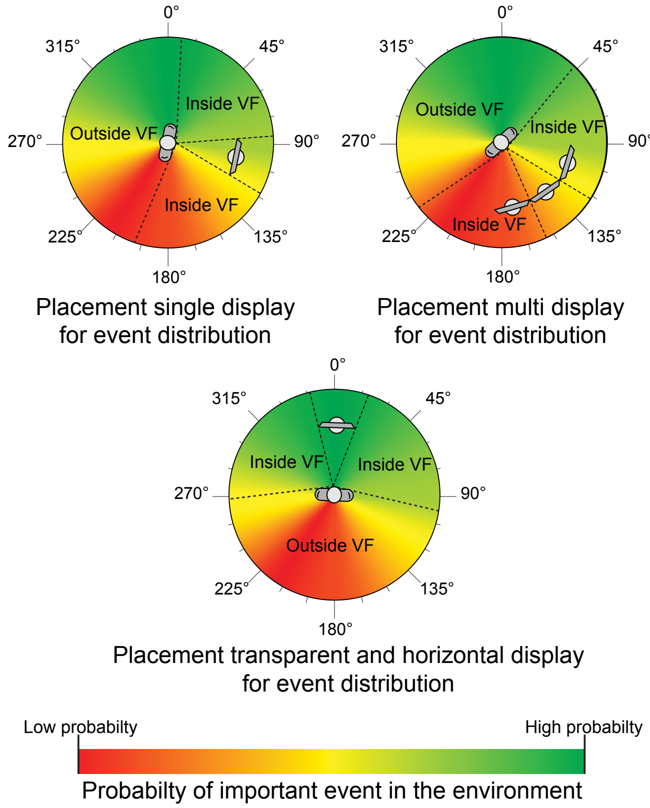

Figure 4. Display positions dependent on event probability. Visual angle and display size influence users' choice of display placement.

visual field on each side for observation. This area, however, only lies in users' far peripheral visual field, which increases the possibility of events going unnoticed. This problem is increased in situations where task complexity is high, since this can narrow users' visual field (cf. [16]).

In order to overcome the problem of occlusion with vertical displays, a large body of work in the field of CSCW and situation awareness suggests using horizontal displays (e. g. tabletop displays, [13]). Horizontal displays allow users to position themselves centered in areas where important events might occur. While this is beneficial for situation awareness and collaboration, such as face-to-face communication, other challenges arise. In contrast to vertical displays, content displayed on horizontal displays is less visible to others not standing close to the display. This is especially important in situations where others need to observe actions on the display (e.g., command-and-control centers, cf. [13]) . Additionally, horizontal tabletop displays can lead to ergonomic challenges since users constantly have to lower their head [13].

Transparent displays, as proposed in prior work (e. g. [19, 22]), offer a potential solution to these challenges. They allow users to position themselves so that potentially important areas in the background lie in their central visual field. Additionally, they allow users to simultaneously observe on-screen content and the environment behind the display. However, having screen content and the background in the central or near peripheral visual field might distract users.

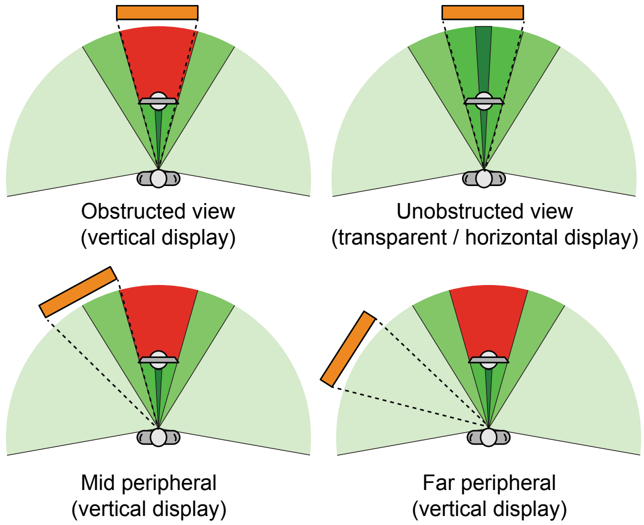

Figure 5. Display configurations and event locations we tested. Orange marks event locations, red the obstructed visual field.

Therefore, our experiment contained conditions comparing typical display configurations with participants observing important events in different positions with respect to the display. Figure 5 illustrates the scenarios we aimed to test, including when the view on the environment behind the display is or is not obstructed and the events occur in an optimal or suboptimal location relative to the display. We aim to inform the design of systems where vertical displays are beneficial (e.g., view on screen content is important), as well as compare transparent displays to horizontal displays. Additionally, we aim to answer the question if transparent displays are beneficial for awareness or if the distraction from the environment behind the display and any resulting decrease in performance outweighs potentially advantages.

METHOD

We conducted an empirical study in order to explore the influence of display transparency and configuration on task performance and users' ability to observe stimuli in the background. Therefore, we tested a dual-task scenario, with participants primarily focusing on the task performed on a display in front of them while simultaneously observing the background for target stimuli. Participants were performing tasks with 5 different display configurations. Configurations included a transparent display with a conventional display in three different configurations, i. e. positioned and rotated at 0°, 30° and 60°, as depicted in Figure 6. Additionally, we used a transparent display and a horizontal display. The transparent display and the horizontal display were positioned between participants and the background area they had to observe.

Participants

We recruited 20 paid participants (5 female) from a local university, aged between 20 and 33 years ($MDN = 26$ years). They were typical display workers ($M = 7.7$ h per day, $SD = 1.9$ h). All had normal or corrected to normal vision (based on self-reports) and had no prior experience with transparent displays.

Apparatus

The study was conducted in a calm experimental room with controlled lighting. We used a backprojected display positioned in front of participants as both, opaque and transparent, display. As a projection surface, we used a 22" sheet of polymer-dispersed liquid crystal (PDLC) switchable diffuser (Kewei Films Non-Adhesive Smart Glass), mounted on a lasercut acrylic frame. The switchable diffuser can be toggled between transparent and opaque (i. e. diffusing incoming visible light) by applying voltage to it (110 VAC). In transparent (activated) state, the switchable diffuser offers a visible light transmission of approximately 82% (5% when deactivated, according to specification). It serves as a projection surface in transparent and opaque state, and maintains resolution and comparable brightness and contrast in both states. For projecting onto the switchable diffuser we used a Benq W1060 DLP projector (resolution 1920 × 1080 pixels, 2000 ANSI lumens). The projector was positioned behind the display and carefully adjusted for each participant to avoid glaring or blending them. Positions of the display were marked to ensure consistency across participants.

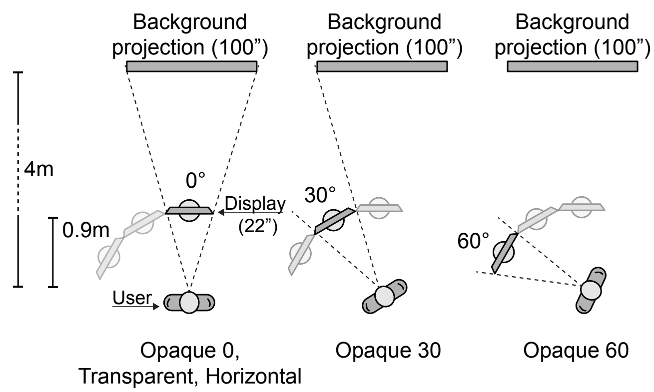

Figure 6. Experimental setup and display configurations used in the experiment. The opaque display was oriented at all three angles, whereas the transparent and the horizontal display were only positioned directly in front of participants.

We decided to apply this combination of switchable diffuser and projector, as it has a much higher level of transparency than commercially available transparent LCDs (e. g. about 15 - 20% for the Samsung LTI330MT02). We believe our experiment would be severely biased with a display technology (i. e. transparent LCDs) that is inferior to current non-transparent displays, especially since we consider the limited features of current commercial transparent displays as a limitation that will be overcome in the near future. Figure 7 shows a side-by-side comparison of the display in opaque and transparent state.

For displaying background stimuli behind the display, we used a 100" (2.54 m) wall projection (resolution 1280 × 800 pixels), at a constant distance of 4 meters to participants, illustrated in Figure 6.

Figure 7. The projected display used in the experiment for performing the primary task, in opaque (*left*) and transparent state (*right*, stimuli of background task, letter "M", clearly visible). Glaring effects in transparent state (light blue bottom) are photography artifacts and not visible to participants.

Design

We used a within-subjects repeated measures design with *display configuration* as independent variable. *Display configuration* consisted of 5 levels, *Opaque 0*, *Opaque 30*, *Opaque 60*, *Horizontal* and *Transparent*, illustrated in Figure 6, counterbalanced using a Latin square. For *Opaque 0*, *Transparent* and *Horizontal*, the display was positioned in front of the participants, i. e. between participants and the projection. Participants were allowed to lean over to see the background display for *Opaque 0*, however they were instructed to not change the position of the chair or to stand up. *Opaque 30* represents a contiguous setup distributed on multiple depths, whereas *Opaque 60* represents a non-contiguous setup (cf. [34, 33]). As primary task, participants performed a square-click task (cf. [31, 28]). As secondary task, we displayed random stimuli (i. e. letters) on the background projection and participants had to respond to specific ones.

Tasks

We adopted an attention-demanding primary task, the *square-click task*, usually applied in ambient information and peripheral interaction experiments (e.g., [31, 28]). In this game-style task, a square (150×150 pixels, approx. 4×4 cm) appears at random locations on the display in front of participants. Each square includes a random single-digit label and can be resolved by clicking the square and inputting the correct number before the next square appears. If no response is given, the trial is marked as error. New squares appeared at a random interval of 2 or 2.5 seconds. We controlled randomization for each condition to result in 120 trials, therefore each participant performed 600 trials overall (5 condition $\times$ 120 trials) during the experiment. We chose this task since we believe it provides a good balance between light to moderate cognitive load and visual load, while requiring participants' full attention.

As secondary task, participants had to observe the background for a specific target stimulus, the letter "K" in our case, appearing at random locations in the background. As soon as participants identified the target stimulus, they had to indicate this by pressing the space bar within a timeframe of 2 seconds. Distractor letters were displayed additionally to the target stimulus, with always one stimulus visible at a time. New stimuli were presented every 1 to 2 seconds (randomized). A total of 45 target stimuli were presented to users, with a target to distractor ratio of 1:7.

This task is an adoption of the n-back task, typically used in psychological and HCI experiments (cf. [7, 3]). In the n-back task, stimuli (typically letters) are displayed centered at a screen. For each presented stimulus, participants must indicate if the current stimulus matches a stimulus displayed n trials (e.g., 1, 2, 3) ago, while ignoring other distractor stimuli. By varying the number n, the working memory load can be adjusted, with workload increasing as n increases. Our secondary task can be seen as a 0-back task with random stimuli location, its mental load therefore is relatively low. We chose this task since it requires very little learning and resembles a scenario in which participants know immediately to which events they have to respond and which to ignore. Furthermore, we opted for a 1-back task with low mental demand since high mental demand (e. g. through higher n) can narrow users' visual field in which they notice events (cf. [16]).

Hypotheses

We performed the experiment with respect to the following hypotheses. We expected that the amount of effort needed for simultaneously observing the background for target stimuli would impact primary task performance. Additionally, we hypothesized that the visual distraction from the background would influence especially task performance on the transparent display negatively. In summary, we expected *Opaque 30* and *Horizontal* to be beneficial for primary task performance and the observational secondary task, whereas distraction to influence primary task performance for *Transparent* negatively. Due to their rotational configuration, we expected primary task performance to be lower for *Opaque 0* and *Opaque 60*.

Therefore, we hypothesised from best to worst (i. e. *Opaque 30*, *Horizontal*, *Transparent*, *Opaque 0*, *Opaque 60*), which resulted in the following hypotheses:

H1. *Opaque 30* will result in higher primary task performance than *Opaque 0* and *Opaque 60*.
H2. *Transparent* and *Horizontal* will result in higher primary task performance than *Opaque 0* and *Opaque 60*.
H3. *Opaque 30* and *Horizontal* will result in higher primary task performance than *Transparent*.

Additionally, we formed two hypotheses regarding participants' ability to observe stimuli in the background (i. e. secondary task performance). We expected the rotational configuration of *Opaque 0* and *Opaque 60* to influence secondary task performance negatively. We did not expect any differences between *Opaque 30*, *Horizontal* and *Transparent*, since primary and secondary task stimuli appear within participants' near to mid peripheral visual field.

H4. *Opaque 30* will result in higher secondary task performance than *Opaque 0* and *Opaque 60*.
H5. *Transparent* and *Horizontal* will result in higher secondary task performance than *Opaque 0* and *Opaque 60*.

Procedure

Participants were briefly introduced to the setup and the experiment and completed a demographic questionnaire. Participants first performed a training session for the primary task, always with *Opaque 0*. They were asked to *complete the primary task as fast as possible without making any errors*. Afterwards, participants completed a short training session for the secondary task.

Subsequently, participants performed the task in all conditions, counterbalanced using a Latin square. Before each condition, participants were seated in front of the current display configuration and instructed to start the condition at will by clicking a button. Each condition took approximately 6 minutes. After each condition, participants completed a questionnaire based on Tyrrell's six scores of mental and visual fatigue ([37], cf. [5]), with answers on a seven point Likert scale of strongly disagree (1) to strongly agree (7). Additionally, they answered questions regarding overall distraction and potential usage of the system. Furthermore, they were asked for general comments on the display configuration they just used. After the experiment (duration approximately 60 minutes), participants were debriefed and compensated.

Data collection
We collected primary and secondary task data for times and error using custom logging software. All input events were logged, including time to resolve squares in the primary task, and errors. For the secondary task, correct responses including time information (starting from appearance of the target stimuli) as well as errors were recorded. Errors were counted when participants missed a target stimulus or responded to a distractor.

RESULTS
In this section, we report on our quantitative results from primary and secondary task as well as qualitative results from collected post-condition questionnaires.

Primary task results
Trial completion time was calculated from appearance of a square to participants correctly resolving it by clicking on it and inputting the correct number. Error rates were measured as the number of not resolved squares.

Trial completion and errors were analyzed using two individual 5× (*display configuration*) one-way ANOVAs ($\alpha = .05$) on the dependent variables trial completion time (averaged trial completion times, only correct trials) and error. Results did not show significant differences between conditions, neither for trial completion time nor error. Participants resolved each square at an average of 1.61s ($SE = 0.01s$), without differences between conditions ($F(4,95) = 0.168$, $p = .954$), as depicted in Figure 8. On average, participants made 8.19 errors ($SE = 0.55$) per condition (of 120 trials), across all conditions ($F(4,95) = 0.063$, $p = .993$).

Discussion
Interestingly, participants' primary task performance was not influenced by the display configuration. First, this suggests that participants followed our instructions to focus on the primary task and handle background stimuli as secondary task. Secondly, and more surprisingly, participants were *not* influenced by the background task for conditions with the transparent display. As reflected in participants qualitative ratings, they

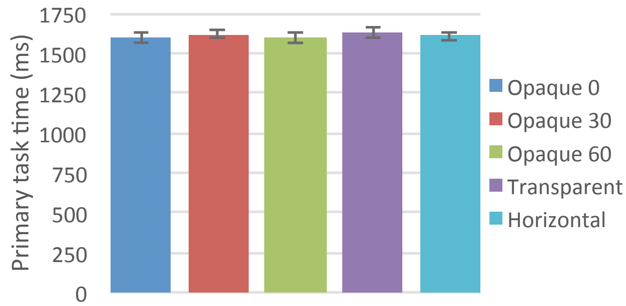

Figure 8. Primary task trial completion times in milliseconds across all conditions. Error bars indicate standard error.

did not feel distracted. Our results show an even distribution of trial completion time among all conditions. Statistical analysis indicates that the minor differences in trial completion time between conditions are of random nature, which contradicts our hypotheses formed with respect to primary task performance (*H1 - H3*).

Secondary task results
We analyzed secondary task performance with the dependent variables being *number of detected background* stimuli and *detection delay*. False-positive errors occurred very rarely (48 in total for all conditions and participants) and were therefore not analyzed. Both dependent variables were analyzed using individual one-way ANOVAs ($\alpha = .05$).

The stimulus detection delays were not statistically different across conditions ($F(4,91) = 0.19$, $p = .943$) with a mean of 1.08s ($SE = 0.02s$). Means across conditions are depicted in Figure 9.

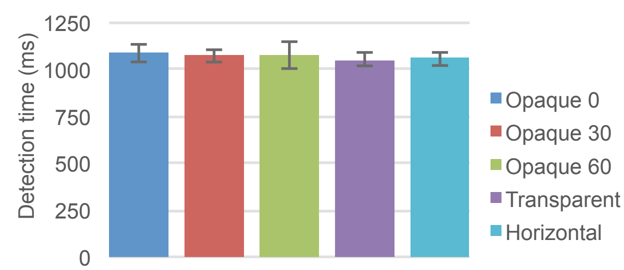

Figure 9. Secondary task stimuli detection delays in milliseconds across all conditions. Error bars indicate standard error.

An analysis of the number of detected background stimuli showed a significant main effect ($F(4,95) = 38.375$, $p < .01$). Mean values and standard errors are illustrated in Figure 10. A Tukey post-hoc test revealed that the detection rate across several conditions was significantly different. Participants detected significantly less stimuli for *Opaque 0* ($M = 24.6\%$, $SE = 3.7\%$) and *Opaque 60* ($M = 30.1\%$, $SE = 5.4\%$) than for any other condition (all $p < .001$). For *Opaque 30* ($M = 55.33\%$, $SE = 4.4\%$), the detection rate was lower than for *Transparent* ($M = 81.8\%$, $SE = 2.4\%$, $p < .001$) and *Horizontal* ($M = 70.4\%$, $SE = 3.6\%$, $p = .067$, $p < .001$). The difference of 11.4% between *Transparent* and *Horizontal* was not statistically significant ($p = .274$).

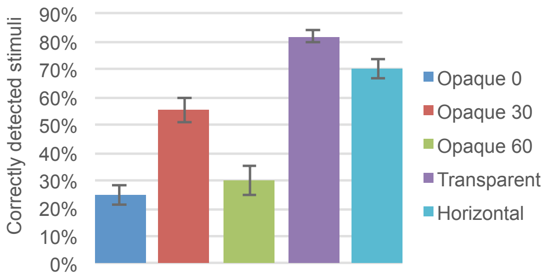

Figure 10. Percentage of detected background stimuli during secondary task. Error bars indicate standard error.

Discussion

In contrast to primary task performance, results were highly different across conditions for secondary task performance, more specifically detection rate. Participants had problems detecting background stimuli especially during *Opaque 0* and *Opaque 60 conditions*. Therefore, hypothesis *H4* (*Opaque 30* better than *Opaque 0* and *Opaque 60*) is supported.

During the experiment, we saw participants having different strategies for *Opaque 0*, with the most common strategy being to lean over to see both screens. However, even for those participants, background stimulus detection rates were mostly around 35%. Only one participant (P2) reached 50% with *Opaque 0*, but also performing exceptionally well in the other conditions (e. g. *Transparent* and *Horizontal* with 93%). With *Opaque 60*, the background was outside participants' mid peripheral visual field, making it hard to focus on both tasks simultaneously.

Hypothesis *H5* (*Transparent* and *Horizontal* better than *Opaque 0* and *Opaque 60*) can also be supported. Additionally, we saw that participants detected nearly 30 percentage points more background stimuli for *Transparent* than for *Opaque 30*. This was surprising, since we expected that the ability to have both displays in the mid to near peripheral visual field for *Opaque 30* would give participants the ability to achieve high background stimulus detection rates.

Lastly, we saw that the difference in detection rate between *Transparent* and *Horizontal* was not significant, although the average detection rate differed by 11.4% in favor of *Transparent*. For *Horizontal* and *Opaque 30*, the background is visually offset to the screen. It seems like the horizontal rotation of *Horizontal* had less impact on secondary task performance than the vertical rotation of *Opaque 30*.

Qualitative results

We analyzed data gathered from post-condition questionnaires using a series of Friedman tests. Participants answered questions on a 7-point Likert scale, ranging from strongly disagree (1) to strongly agree (7). Results showed significant differences for answers to two questions, which were "My back and/or neck hurts from sitting in this position while performing this task." ($\chi^2(4) = 17.091$, $p < .01$) and "I would use the system I just tested." ($\chi^2(4) = 38.906$, $p < .001$). Answers for the other questions did not differ significantly across conditions.

For gaining further insights, we conducted a series of Wilcoxon Signed-Rank tests (Bonferroni adjusted $\alpha = .005$). For the question if participants felt that their back hurt, results showed significant differences between *Transparent* ($M = 1.70$, $SD = 1.30$) and *Opaque 0* ($M = 3.80$, $SD = 2.21$, $p < .005$), and *Transparent* and *Opaque 30* ($M = 2.80$, $SD = 1.88$, $p < .005$). No other significant differences to *Horizontal* ($M = 2.35$, $SD = 1.57$) or *Opaque 60* ($M = 2.70$, $SD = 1.53$) were present.

Furthermore, participants' ratings on the usage of the system revealed significant differences between conditions (best to worst: *Transparent*, *Horizontal*, *Opaque 30* and *Opaque 60*, *Opaque 0*). In more detail, there were differences between *Transparent* ($M = 4.05$, $SD = 1.36$) and *Opaque 0* ($M = 1.60$, $SD = 1.57$), *Transparent* and *Opaque 30* ($M = 2.35$, $SD = 1.31$), and *Horizontal* ($M = 3.45$, $SD = 1.90$) and *Opaque 30* (all $p < .005$). Difference between *Transparent* and *Opaque 60* ($M = 2.35$, $SD = 1.63$) did not reach statistical significance ($p = 0.0053$).

Discussion

In general, participants' scores on Tyrell's questions on physical and mental fatigue were low (overall $M = 3.02$, $SD = 1.89$), showing that they could perform all tasks without too much effort. Participants' preference for some of the conditions is reflected in the comments we received as part of the questionnaire, such as P6's written comments to *Opaque 30* "This system is not as good as the transparent display, but better than all other configurations I tested.", or "Because I experienced the see-through display already I don't want to use the system I just tested." or P8 when starting the *Transparent* condition "This is awesome, I want one of these.". While we believe that the novelty of the transparent displays positively influenced the ratings, we saw participants acknowledging the usefulness of the transparent displays.

The horizontal condition was also perceived positively, though participants complained about the constant head movement (up and down). This is reflected in the comments we received such as "It seemed to generate better results (higher hit rate), but at the same time it felt more stressful (for the eyes and brain)." (P2), "Most comfortable position, can give equal attention to both the tasks." (P5, with a background stimulus detection rate of 93% for *Transparent* and 68% for *Horizontal*), or "Always looking down and up again is pretty annoying." (P11).

DISCUSSION

In our experiment we found that the transparent display and the horizontal display were superior in the observational secondary task compared to a conventional display, independent of its angular position. This is especially surprising for conditions with the conventional display tilted only up to the degree where display and background are equally visible (i. e. edge aligned, cf. [29]). We expected that when both the primary task display and the background are within the near and mid peripheral visual field, participants would perform equally well as with the transparent or horizontal displays. This makes us believe that users ability to perform a typical display worker task while simultaneously observing a busy environment *beside the display* results in poor observational performance.

Although our participants were able to anticipate the occurrence of target events, they did not identify more than 55% of these events with *Opaque 30*. We believe this is due to the angular difference in visual field between primary and secondary task. Although the visual separation is as small as possible with a conventional (opaque) display by placing it right beside the observation area with *Opaque 30*, results show that even this small separation decreases secondary task performance significantly, especially when compared to *Transparent*.

Comparing *Opaque 30* and *Horizontal*, we believe the decreased performance for *Opaque 30* could be a result of differences in visual area. Both displays were 16:9 (i. e. landscape orientation), thus the visual area that needs to be observed is bigger for *Opaque 30* + Projection compared to *Horizontal* + Projection. Therefore, it might have been easier for participants to see both displays simultaneously for Horizontal.

While we acknowledge that the events in our secondary task appeared in very frequent order, we believe that these results give insights for systems where users have to perform a regular display task and observe the environment simultaneously.

We did not see a decrease in primary task performance, as found by Tan and Czerwinsky [34]. This is most likely due to the difference in tasks, since also the detrimental effects found in their work were rather small. For secondary task performance, however, effects were rather large for our experiment. This suggests that the decrease in secondary task performance is guided largely by visual separation, but likely also task specific. In contrast to our work, Tan and Czerwinsky used a notification-based secondary task, which allows for easy detection of stimuli because of their sudden appearance and the lack of distractors.

Implications and recommendations

From our quantitative and qualitative results, we draw the following implications and recommendations.

- **Proximity to visual field is important:** Users' ability to observe the environment for events is highly influenced by offset in visual angle. If the location of an event is known, the proximity in terms of visual angle must be matched as closely as possible. However, even then, our results show that when working on a regular-sized display, chances are high that users might miss up to half of important events. Therefore, conventional displays should only be used for dual-tasks when the events in the background are clearly distinguishable from other ones and do not appear at a high frequency. If users work on even larger screens (e. g. $>$35"), the possibility of missing events increases.
- **Horizontal displays are better for background awareness than conventional displays:** When designing for dual-task usage, horizontal display should be given preference over a conventional display with offset. The horizontal display allows users to keep their primary task performance consistent while highly increasing users' ability to observe the background and identify events. Our horizontal display was slightly tilted to be edge aligned with the background, as was the conventional display in the *Opaque 30* condition. The horizontal display covered less visual area than the conventional display, mostly because of its orientation, which was beneficial for participants. Decreasing the visual area of conventional displays through tilting, however, is not feasible.
- **Transparent displays free users' visual field while keeping primary task performance constant:** Users can perform attention demanding tasks equally well on transparent displays as on traditional opaque displays. Furthermore, transparent displays highly increase users' ability to observe the background compared to a conventional display, *independently* of its rotation or position.
- **Users can choose between transparent and horizontal displays:** We did not find any statistical differences between these two display configuration. Therefore, users as well as designers of system can use both transparent and horizontal displays without sacrificing on primary task performance or ability to observe the background. Using a transparent display can be beneficial in situations where users prefer vertical displays (e. g. to increase the area from which the display is visible and increase comfort) over horizontal displays. However, our qualitative findings and suggest potential negative impact on comfort and posture of horizontal displays for longer-term usage. This needs to be subject of future investigation.

In general, we believe that the impact of angular offset from the central peripheral field highly influenced users ability for observation. Our results show that, while participants performed the primary task equally well across all conditions, their secondary task performance decreased with increasing visual field. The only exception to this is *Opaque 0*, where participants had to take a rather large effort to also see the secondary task. We included this condition, knowing that it was impossible to see the background without additional effort to see users reaction and observe strategies. Participants tended to lean over to find to *optimal* viewing angle to see both displays. However, this additional effort drastically decreases secondary task performance. Therefore, in situations where the location of events in the background can be anticipated, even with optimal viewing position of a traditional display (i. e. *Opaque 30* in our experiment), users should be aware of the high probability of missing events in the background.

The very large display experience

Researchers in HCI often argue that increasing screen real estate increases efficiency and opens a wide range of applications. However, typical screens are more in the range of 20" - 30", and not coming close to the size of many TV sets at home. Only for very few occasions there seems to be justification for users to sit in front of a large wall of displays for their daily work (e. g. workers in stock exchanges observing a multitude of graphs simultaneously). We argue that one of the reasons conventional displays are not as large as they could be is because users would feel uncomfortable sitting behind a 150" wall of displays. Therefore, having a (at least partly) transparent display (e. g. [22]) potentially increases user acceptance and efficiency.

Visual interference

In our experiment, users could see the background as well as the primary task simultaneously during conditions with the transparent displays. While we found that distraction had no impact on task performance, we did not test for situations where on-screen contrast is low because of transparency. We believe that in order for transparent displays to be used in uncontrolled environments with arbitrary background, issues of visual interference need to be resolved. While outside the scope of this work, other research suggests several ways to eliminate visual interference on transparent displays such as heads-up-displays (e. g. [18, 32]). Incorporating these techniques and evaluating various display configurations (including transparent displays) is a necessary step to evaluate the usability of transparent displays.

Limitations and future work

Our current experiment featured only a single type of background stimuli and primary task. While we believe that our results give valuable insights into users' ability of performing dual tasks with varying display configurations, more diverse stimuli need to be tested, potentially with real actors such as by Reetz et al. [30]. Furthermore, the impact of stimuli with different visual behavior (e. g. looming stimuli) needs to be included in future studies. Additionally, while our participants were well aware of the fact that events occur frequently, it would be interesting to investigate users ability to recognize unforeseen events. This, however, requires a longer investigation and presumably should be performed as a field experiment gathering user experience data rather than a lab study. Performing our experiment in a very controlled manner, however, gave us the ability to avoid other confounding factors and gave us clear insights into users' performance under the tested conditions.

Conclusion

We investigated the influence of display transparency on task performance in a dual-task scenario. Our results show that transparent and horizontal displays increase users' ability to observe events in the environment while keeping task performance constant. In our experiment, participants did not show a decrease in task performance for transparent displays, despite not shielding them from potential distraction in the background. Furthermore, we show that an increase in visual angle between display and event location negatively impacts observation rate. Our findings indicate that users can choose freely between transparent and horizontal displays based on use case without sacrificing task performance.

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