# An Exploration of Interaction-Display Offset in Surround Screen Virtual Environments

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**ABSTRACT**

We present a study exploring the effect of positional offset between the user's interaction frame-of-reference (the physical location of input) and the display frame-of-reference (where graphical feedback appears) in a surround-screen virtual environment (SSVE). Our research hypothesis states that, in such an environment, task performance improves given an offset between the two frames-of-reference. In our experiment, users were asked to match a target color using a 3D color widget under three different display-interaction offset conditions: no offset (i.e., collocation), a three inch offset, and a two foot offset. Our results suggest that collocation of the display and interaction frames-of-reference may degrade accuracy in widget-based tasks and that collocation does not necessarily lead the user to spend more time on the task. In addition, these results contrast with previous studies performed with head-mounted display (HMD) platforms, which have demonstrated significant performance advantages for collocation and the "direct manipulation" of virtual objects. Moreover, a previous study with a different task performed in a projector-based VE has also demonstrated that collocation is not detrimental to user performance. Our conclusion is that the most effective positional offset is dependent upon the specific display hardware and VE task.

**Keywords:** 3D interaction, collocation, interaction-display offset.

**Index Terms:** I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction techniques; H.5.2 [Information Interfaces and Presentation]: User Interfaces—Evaluation/methodology

## 1 INTRODUCTION

Building effective and usable interfaces for virtual environment applications is a common goal among VE application developers. Many different interaction technique choices depend on application, VE hardware, type of user, and other factors. In addition, interaction techniques often have parameters that must be carefully chosen to maximize user performance. Finding appropriate values for these parameters is often a challenging task. Thus, providing guidelines for choosing suitable interaction techniques and technique parameters is a worthwhile pursuit. Those techniques centered on the user's body constitute a commonly described class of interaction techniques found in VEs. For example, a user can use his or her hands to spatially interact with virtual objects and widgets. A fundamental question that has gone relatively unexplored in the class of body-centered interaction techniques asks where ought a given virtual object be placed with respect to the user.

According to Mine [5], virtual objects that are collocated with the user's body provide higher levels of performance for docking tasks than when an offset is present between the user's body and the virtual object. However, Mine's work was conducted using a head mounted display (HMD). In such a VE platform the user cannot see his or her physical body. Therefore, it is important to explore whether Mine's findings extend to surround screen VEs, where the user can see his or her body and virtual objects cannot occlude the line of sight to the hands or input devices. Such an exploration was undertaken by Paljic, et al. [6] Using a projector-based Responsive Workbench, they found that a zero or minimal offset between the interaction and display frames-of-reference minimized time-to-completion in a docking task similar to Mine's technique.

Our intuition, contrary to the results of Mine and Paljic, was that a positional offset could improve performance in our surround-screen VE by minimizing the visual interference of the user's own body. To explore how positional offsets affect user performance in a surround-screen virtual environment (SSVE), we conducted an experiment where the user was asked to match colors using a 3D color-picking widget, a representative spatial interaction task chosen from a frequently used application at the Brown University SSVE: CavePainting [3]. During the experiment, different translational offsets between the user's interaction frame-of-reference (the physical location of input) and the display frame-of-reference (where graphical feedback appears) were presented as conditions. Specifically, users were asked to match a target color under three different conditions of the widget's displayed feedback relative to a fixed interaction frame-of-reference: zero offset, three inches of offset, and two feet of offset. We hypothesized that because the user can see his or her body in surround-screen VEs, a non-zero positional offset will improve user performance in completing a widget-based spatial interaction task.

In the next section, we discuss two related VE interface evaluations to provide context for our experiment. Section 3 describes our experimental procedure in detail. Section 4 presents the results of our experiment while Section 5 provides a discussion of their implications. Finally, Section 6 proposes ideas for future work and concludes the paper.

## 2 BACKGROUND AND RELATED WORK

Many approaches have been used to evaluate VE interaction techniques. A broad overview of the motivation, methods, and taxonomy of VE interface evaluation can be found in Bowman, et al. [1] Several studies have introduced the offset between the display and interaction frames-of-reference as an experimental condition. We present a discussion of their results.

Mine, et al. [5] conducted an experiment exploring the difference between manipulating virtual objects that are collocated with those that have a positional offset. Their results showed that users performed better under the collocated condition. This experiment is closely related to our work except Mine used an HMD while our experiment was conducted in a SSVE.

Paljic, et al. [6] performed a study most similar to the current work in terms of VE display platform. They employed a Respon-

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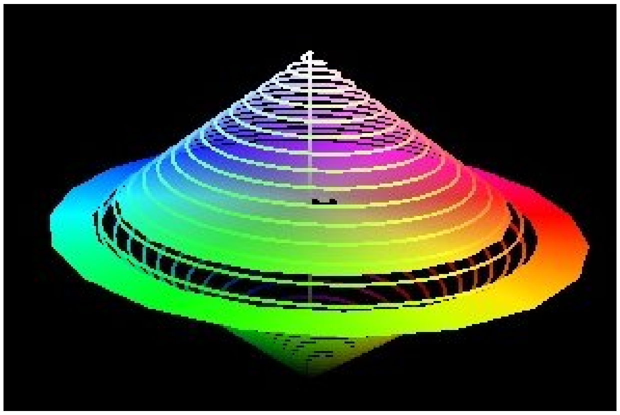

Figure 1: CavePainting color-picking widget.

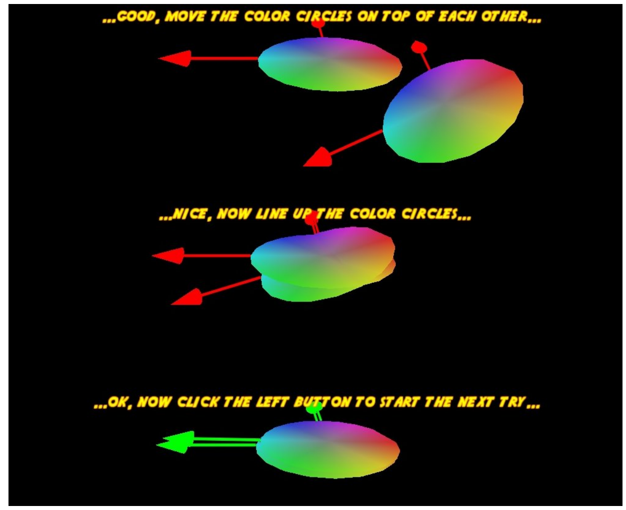


Figure 2: Procedure for the centering task.

sive Workbench[1] device which, much like the Cave-based SSVE used in our study, projects images onto screens mounted in front of the user. In contrast to the HMD display utilized in Mine's study, this allows the user to see his or her hands while interacting with the VE. Paljic and colleagues chose an object docking task similar to Mine's. Subjects were asked to use a tracked pen device to translate a virtual sphere to one of nine target spheres. Offset between the tip of the tracked pen device and the virtual cursor used to grab the object sphere was introduced as a factor with four levels: 0, 20, 40, and 55 cm (0, 7 $\frac{7}{8}$, 15 $\frac{3}{4}$, and 21 $\frac{5}{8}$ in). Target sphere was another factor in the experiment. They measured time to completion and found that the two shorter offset conditions performed significantly faster than the two longer offsets.

## 3 Experiment

### 3.1 Hypothesis

An experiment was designed to test the effect of varying the offset of the display frame-of-reference with respect to a fixed interaction frame-of-reference for a 3D widget-based task. We chose a 3D color-picking widget based on the one deployed in the CavePainting application [5]. The widget maps the position of the user's hand to a color. Interaction using this widget is representative of many types of 3D spatial interaction tasks requiring users to move a virtual cursor in 3D space. Color-matching was chosen as an example task utilizing the color-picking widget. Our hypothesis for this study was that a translational offset between interaction and display frames-of-reference would improve user performance for the color-matching task. This hypothesis was justified based on a fundamental characteristic of surround-screen VE systems: the user's body or hand-held tracking device cannot be occluded by computer graphics imagery. In the collocated case, the physical position of the user's hand will be sufficiently close to the displayed feedback of the widget to prove distracting and thus decrease performance.

This hypothesis goes against the results of Mine's study [5] which stated that collocation is more efficient than with a positional offset. However, Mine used an HMD in his experiments where the subject could not see his or her hands or body. Paljic's study, in which the subject could see his or her body, reached a similar result as Mine: the collocated condition performed among the best of all conditions. Paljic adds an important detail: performance is no worse at 20 cm (7 $\frac{7}{8}$ in) offset than with collocation (zero offset).

[1] http://www.imk.fraunhofer.de

### 3.2 Experimental Design

#### 3.2.1 Participants

Twenty-nine subjects (15 male, 14 female) completed the study. 17 out of 29 subjects wore glasses and two subjects were left-handed. Subjects were drawn from the Brown community at large and were solicited via announcements posted around the Brown University campus. Each subject was paid at least $10 for approximately an hour of his or her time, though several subjects took slightly longer and were paid an additional $10 per hour pro-rated.

#### 3.2.2 Apparatus

The surround-screen display used in our study is a four-walled Cave-like device [2], driven by a five-node cluster with Intel Xeon 2.8 Ghz processor machines using the cluster synchronization platform described in [4]. Active stereo imagery was provided via Nvidia FX 3000G graphics cards synchronized by infrared with Stereographics CrystalEyes3 LCD shutter glasses. The physical size of each wall was 8 ft. squared with a display resolution of 1024 x 768. Four Marquee Electrohome 9500LC projectors, one per wall, provided images updated at 85 Hz (42.5 Hz for each eye). The brightness of each projector was approximately 200 lumens. Head and hand six degree-of-freedom position and orientation information was acquired using Polhemus FASTRAK magnetic trackers. The head tracker was attached to the side of the Stereographics glasses. The hand tracker was affixed to a wireless mouse, which provided several buttons and a two degree-of-freedom joystick to support interaction.

#### 3.2.3 Procedure

The basic task of the experiment was color-matching using the CavePainting [3] color picking widget. The widget operates as follows. Using cylindrical coordinates in the interaction frame-of-reference, the user's hand position determines a point in HSV color-space: the hue of the color is determined by the angular position around the cylinder, the saturation by the radial distance, and the value by the height. In the display frame-of-reference, a double cone is rendered with a spiral wire-frame. A spherical cursor colored with the current color and outlined in black is rendered at the current color's position in the widget. Additionally, an isoplane of constant color value (i.e. brightness) equal to the current color's value is rendered (see Figure 1).

For the task of color matching, two horizontally-adjacent rectangular blocks (swatches) were rendered slightly above the color-picking widget. One of the boxes was colored with the target color and did not change. The other was colored with the currently selected color of the color-picking widget.

Upon arrival to the study location, each subject was first exposed to the VE using a limited version of the CavePainting application. This provided a brief acclimation period to interacting in the VE. The subject was not exposed to the color-picking widget; he or she simply painted with a preset stroke style. Following this acclimation, the subject was taken into another room and asked to read several paragraphs introducing the task, complete a short pre-questionnaire, take a color deficiency screening test, and sign a consent form. Three respondents to the experiment solicitation were rejected as participants because each was unable to pass the color screening test.

Following completion of the pre-questionnaire and color vision screening, each subject was led back into the study area. The subject was shown the tracked mouse device, and specifically the button used on the mouse for indicating color selection during the task. He or she was then asked to begin wearing the stereo shutter glasses and complete a calibration step and a practice session of six color matching trials. The experimenter remained in the study area with the subject to act as a guide during the practice. The calibration step measured the height and reach of each subject. The basis units of Poupyrev's body-centered coordinate system were used as parameters for specifying the interaction frame-of-reference [7]. Specifically, the interaction frame-of-reference was fixed at $\frac{7}{10}$ of the user's height and translated from the subject's center line (the vector from the glasses to the floor) a distance of $\frac{3}{5}$ of a virtual cubit (the user's reach) along the vector perpendicular to the SSVE's front wall. To acquire height and virtual cubit measurements, the subject was asked to stand straight up in the center of the SSVE, reach straight forward, and click the button. The experimenter watched the subject perform this calibration step to ensure that a proper measurement was acquired. After calibration, the subject was asked to complete six practice trials of the color matching task, two per condition. Each practice trial was identical to those performed during the experiment, except they were encouraged to ask any clarifying questions. The ordering of the practice condition blocks was chosen to be the same as it would be during the actual trials.

The protocol for an individual trial is described. The subject first performed a centering task to ensure he or she began in the same position for each trial. This prevented the target location of one trial from affecting the movement distance required to match the target in the subsequent trial. Centering involved two steps: ensuring a standing position in the center of the display (the point on the floor of the SSVE four feet from each wall) and ensuring that the hand, holding the tracked wireless mouse, was positioned at the origin of the interaction frame-of-reference. Standing in the center of the display was defined in terms of the location of the head tracker. If its position projected onto the floor of the display was within six inches of the floor's center, the subject was considered to be standing in a centered position. A cartoon outline of a pair of feet was displayed as a target on the floor to serve as a guide. Once centered in the display, the subject placed his or her hand holding the tracked mouse in the prescribed position and orientation with the aid of two flat discs; one fixed at the target position and the other isomorphically mapped (i.e. 1-1) to the movement of the tracker. Additionally, two 3D arrow models were rendered, one at twelve and one at nine o'clock of the disc. The arrow models were pointing outward in the direction normal to the disc's edge and in the plane of the disc. The arrows were colored red until the subject moved his or her hand within the centering thresholds: two inches of translational offset and 10 degrees of rotational offset (measured as rotational Euler angles around the three primary axes). Once the subject's hand was in the predetermined position, the red arrows became green, and when the subject clicked with the arrows colored green a single trial of color matching followed. See Figure 2 for an outline of the centering task.

The color-picking widget appeared along with the target and currently selected color swatches. The radius of the color-picking widget's extent in the interaction frame-of-reference was fixed at six inches. The radius of the widget in the display frame-of-reference was varied per condition such that the apparent visual angle in the subject's visual field was held constant at $\frac{\pi}{8}$ radians. This was done to ensure that the same amount of information, as measured by the number of pixels, was constant between conditions.

As each subject was informed in the instructions, the goal was to match the target color as closely and as quickly as possible, but that no time limit would be imposed. The subject adjusted the position of his or her hand in the interaction frame-of-reference, moving the cursor in the display frame-of-reference (the color picking widget), until a satisfactory match was achieved. The subject clicked the mouse button to signify he or she was satisfied with the match and a new trial would begin after a short pause.

Following the six practice trials, each subject was given an optional short break after which the experimental trials began with the experimenter leaving the study area. A black curtain surrounding the study area was used to minimize the disturbance caused by ambient light on the perception of the colors provided by the display's projectors. Each subject completed 45 trials, 15 per condition. After completion of these 45 trials, the subject exited the study area and answered the post-questionnaire.

Following completion of the post-questionnaire, the subject was asked to complete a short second phase of the experiment. During this part of the experiment, the fundamental task remained color matching, but the subject was allowed to manipulate the offset distance between the interaction and display frames-of-reference. The purpose of this second phase was to collect performance measurements at distances other than the three offset conditions employed for the first phase and, more importantly, to collect data that might suggest a preferred offset. The procedure for this second phase of the study was identical to that of the first phase except that after the initial centering task the subject was asked to use the joystick on the wireless mouse to adjust the offset to the ideal position. Each trial used an initial offset which was the same as one of the three conditions of the first phase: collocated, three inch offset, or two feet offset. The ordering of these pre-adjustment offset conditions was chosen to be the same as the given subject had already seen during the first part of the experiment. Once the subject was satisfied with the adjusted widget offset, he or she pushed the button on the wireless mouse and the centering task was performed a second time with the centering widget positioned at the new offset. A color matching trial followed with the color-picking widget also displayed at this subject-chosen offset. Each subject completed three practice trials and 15 unguided trials, grouped into blocks of five. After these trials, the experiment was complete.

### 3.2.4 Performance Metrics

Quantitative data was collected from all subjects. Two values were collected per color matching trial: time to completion and chosen color. Time was measured as the duration between completion of the centering task and selection of the color. For the matching task, two more statistics were derived from these measurements: accuracy and accuracy per time. The calculation of a single color distance scalar given two colors was employed in order to simplify the assessment of the degree to which the subject successfully completed the task. A perceptual distance metric

$$d = \sqrt{(2+\overline{R})\Delta R^2 + 4\Delta G^2 + (2-(1-\overline{R}))\Delta B^2} \qquad (1)$$

was used[2], given the target and chosen colors. $\Delta R$, $\Delta G$, and $\Delta B$ are

[2] See www.compuphase.com/cmetric.htm for more information.

all defined as the difference between the target and chosen color components and $\overline{R}$ is an average of the target and chosen $R$ values. The resulting scalar has no unit and the range of the function is between $[0, 2\sqrt{2}]$.

Given the distance measurement, an opposite scalar was derived that increased as the subject's performance at the task improved. The calculation of accuracy is:

$$acc_i = d_{max} - d_i \tag{2}$$

with $d_{max} = 2\sqrt{2}$ and $i = 1$ to $n$ where $n$ is the number of observations. This accuracy scalar was combined with the measured time to derive a single scalar

$$p_i = \frac{acc_i}{t_i} \tag{3}$$

that captures the impact of both measured results on overall subject performance.

In addition to the quantitative metrics, we also provided each subject with a post-questionnaire to gauge his or her preferences and feelings about the experiment. The post-questionnaire was presented as a set of 13 statements each providing a Lickert scale set of multiple choice responses. The responses were "Strongly agree," "Agree," "Neither agree nor disagree," "Disagree," and "Strongly disagree." There were three sections and each of the 13 statements appeared in each section. The sections were prefaced such that each applied to a different interaction-display offset condition. The ordering of offset condition post-questionnaire sections was the same as the presentation of conditions in the experiment.

## 4 Results

The experiment was conducted using a within-subjects design with three offset conditions. Six ordering types were possible. Given 29 subjects, some ordering types are necessarily represented more frequently. If ANOVA is applied to the full set 29 subjects, ordering type emerges as a significant factor in the distance scalar means (F-value 2.8397, Pr(>F) 0.03863). To minimize the impact of this effect during analysis of the measured results, we adopted a balanced design with each ordering type used an equal number of times. Therefore, we discard data for five subjects and used only twenty-four subjects in the analysis, each ordering type being represented four times. We discarded subject data not only to balance the design with respect to ordering types, but also with respect to gender. Balancing the design with respect to ordering type and gender requires that there be exactly two female and two male subjects per ordering type. Thus, one observation must be discarded for those ordering type-gender pairs that have three subject measurements. For these cases, the subject who participated earliest in the course of the overall experiment was removed.

### 4.1 User Performance Results

#### 4.1.1 Descriptives

Figures 3–6 show box-and-whiskers plots for each statistic broken down per condition.

#### 4.1.2 Comparison of means

The null hypothesis under investigation states that the means of each condition are equal. We applied ANOVA analysis to our data to evaluate this hypothesis. Each statistic approaches an intrinsic performance limit. Since the raw measured results are not normally distributed, it is not appropriate to directly apply parametric analysis such as the t-test or ANOVA. Instead, we applied the log function to each raw statistic prior to the analysis in order that the assumption of normality is better satisfied [8].

Each subject tried to match each color exactly once per condition. Thus, we were able to include color as a factor in the analysis.

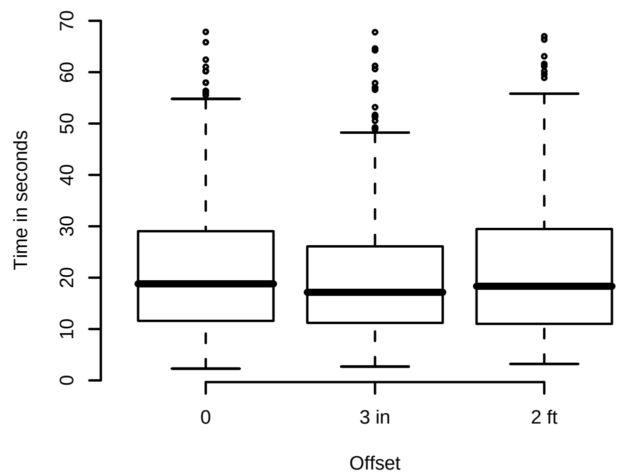


Figure 3: Box and whisker plot showing means, error bars, and outliers for the time measurements per condition.

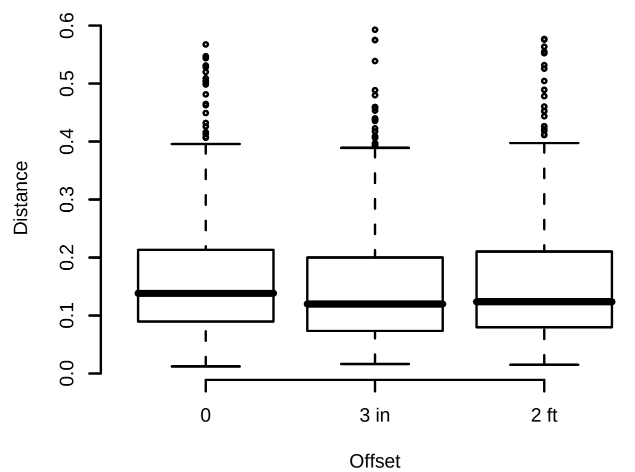


Figure 4: Box and whisker plot showing means, error bars, and outliers for the distance measurements per condition.

We performed two-way, within-subjects ANOVA for the time, distance, and accuracy per time statistics. The factors are the condition and the target color, the former having three levels and the latter fifteen levels. Subject is the known random error. These results are presented in Table 1.

In the distance metric, ANOVA analysis allows this hypothesis to be rejected with Pr(>F) = 0.0224. The other metrics in the matching task do not show significant differences between means. The centering task performance, in which the time was minimized in the short offset condition, demonstrates a strong significance.

The results shown in Tables 2 show that the differences between the collocated and each of the offset conditions is most pronounced, but that little difference exists between the two offset conditions for the color matching task. In contrast, the short offset and collocated

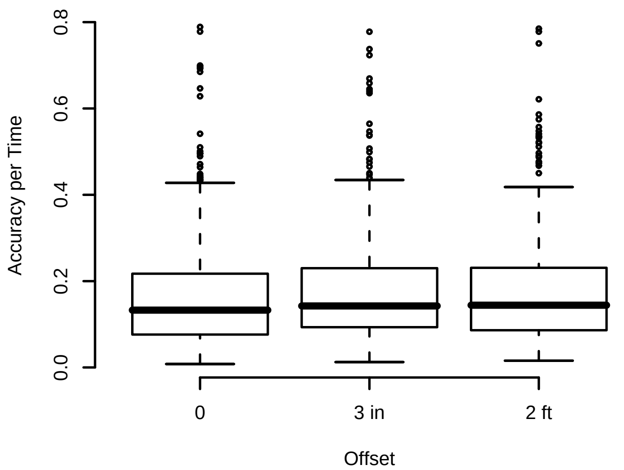


Figure 5: Box and whisker plot showing means, error bars, and outliers for the accuracy per time measurements per condition.

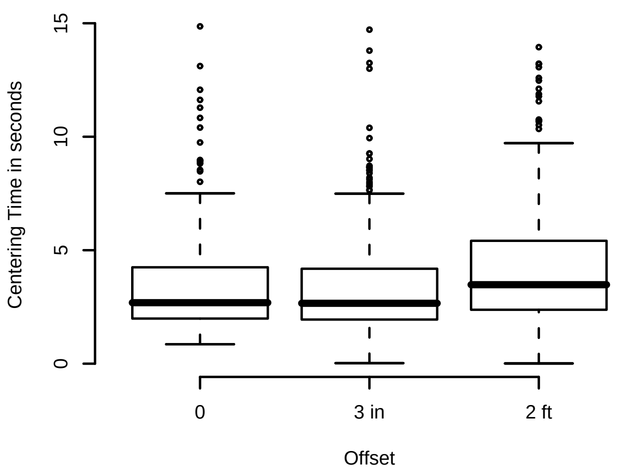


Figure 6: Box and whisker plot showing means, error bars, and outliers for the centering time measurements per condition.

condition perform similarly for the centering task, whereas the long offset condition exhibited definitively inferior performance.

### 4.2 Second Experiment Phase: Widget Placement

The second part of the experiment allowed the subject to specify the offset between the interaction frame-of-reference and the display frame-of-reference prior to each color matching attempt. The purpose of this phase of the experiment was to determine the preferred offset. Descriptive statistics for the offset choice are shown in Table 3. See Figure 7 for a histogram of the chosen offsets. Ultimately, subjects, on average, preferred an offset of $1\frac{1}{3}$ feet.

| Statistic | Factor | $Df$ | F-value | Pr(>F) |
|---|---|---|---|---|
| Time | Offset | 2 | 1.297 | 0.283 |
| | Color | 14 | 7.867 | $2.27 \times 10^{-14}$ |
| Distance | Offset | 2 | 4.13 | 0.0224 |
| | Color | 14 | 20.7 | $< 2.0 \times 10^{-16}$ |
| Accuracy Per Time | Offset | 2 | 1.655 | 0.202 |
| | Color | 14 | 7.108 | $7.98 \times 10^{-13}$ |
| Centering Time | Offset | 2 | 8.2594 | 0.0008614 |
| | Color | 14 | 0.7685 | 0.7033 |

Table 1: Two-way ANOVA results for the balanced subject pool.

| Conditions | Statistic | p-value |
|---|---|---|
| Short vs. Long offset | Time | 2.2635 |
| | Distance | 2.5266 |
| | Accuracy Per Time | 2.1699 |
| | Centering Time | $1.689 \times 10^{-7}$ |
| Collocated vs. Long offset | Time | 0.19872 |
| | Distance | 0.0026733 |
| | Accuracy Per Time | 0.1221 |
| | Centering Time | $1.944 \times 10^{-5}$ |
| Collocated vs. Short Offset | Time | 0.3624 |
| | Distance | 0.0027369 |
| | Accuracy Per Time | 0.2526 |
| | Centering Time | 1.2495 |

Table 2: Paired sample t-test results between each condition for the balanced subject pool. $df = 359$ given 15 color matching pairs for each of the 24 subjects. Bonferroni correction is applied to each p-value.

### 4.3 Post-Questionnaire Results

Results from the post-questionnaire are summarized in Figure 8. We performed ANOVA analysis comparing mean responses between conditions.

## 5 Discussion

Each of the two offset conditions proved to be significantly better, both from user performance and preference points of view. Prior to the experiment, it was posited that the offset conditions would be best as they would minimize distraction during use of the color-picking widget. This hypothesis can be accepted based on the results. No significant difference for any performance metric was found between the two offset conditions. In the post-questionnaire subjects reported that they could not see their hands very much in the short or long offset case and reported less distraction in the short offset. It is likely that the short offset condition is not very distracting. Moreover, in the second experiment phase, subjects rarely moved the widget to an offset greater than the long offset, suggesting that two feet is larger than the optimal offset. The results indicate that performance degrades as display-interaction offset distance is decreased from three to zero inches for this color-matching task.

Although our initial goal was to explore the effect of display-interaction offset on user-performance with the color-picking widget, we ultimately garnered statistical results for the centering task as well. This task is most comparable to the previous results reported by Mine and Paljic. Much like their chosen tasks, the centering task performed prior to each matching trial involved aligning a movable virtual object with one of identical shape fixed in virtual space. For the centering task, our results confirm those found by Mine and Paljic: collocation or a short offset maximizes user

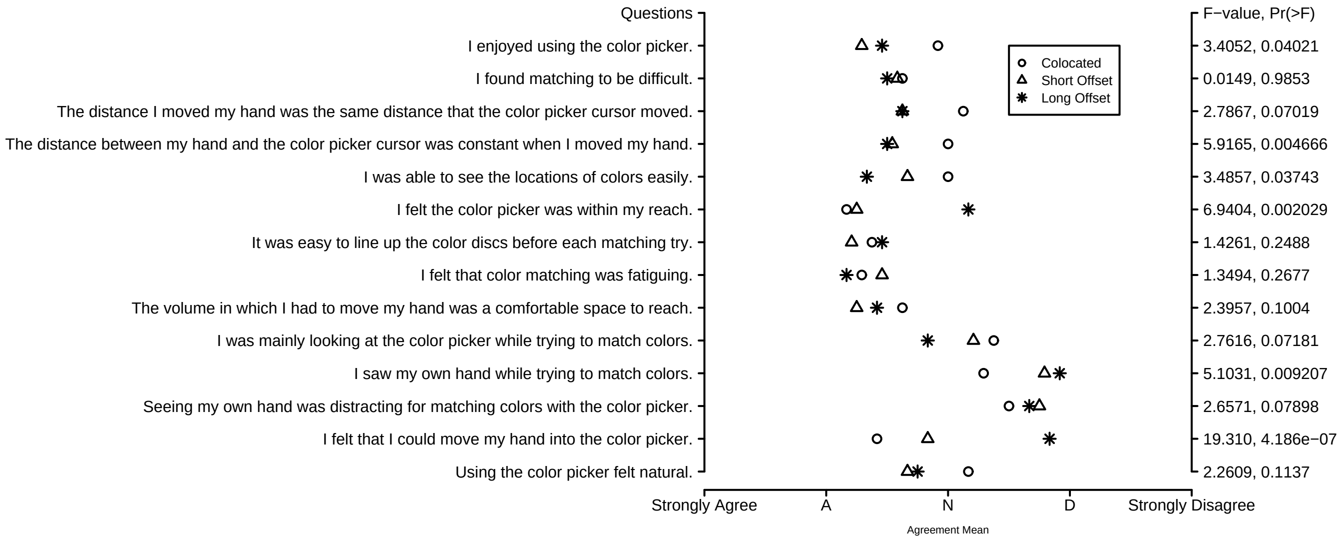


Figure 8: Scatterplot of post-questionnaire Lickert scale responses. Between-subjects ANOVA F-value and Pr(>F) results are presented on the right of each question row.

| | |
|---|---|
| Mean | 1.34 feet |
| Standard deviation | 1.026 |

Table 3: Mean and standard deviation of the actively chosen offsets.

performance.

The results of our analysis for color matching lead to a different conclusion. We believe that the color-picking widget borrowed from the CavePainting application may embody an interaction technique not generalized by previous studies.

## 6 Conclusion

We have presented an experiment that explored how positional offsets affect user performance in a color matching task using a 3D color-picking widget in a surround screen virtual environment. Each trial of the experiment included an object-docking task (centering) prior to the matching attempt. Our results both agree and disagree with previous work. On the one hand, our centering task demonstrates increased user performance with minimal offset. This is in line with previous work, which has hypothesized that shorter offsets between the display and interaction frames-of-reference maximize performance. On the other hand, our analysis of the color matching task reveals that performance at the zero offset condition is worse than at a small or a large offset. We believe this contrast exposes a separate class of task that is not precisely governed by any previous guideline. While object-docking is a coarse task during which the subject must not necessarily look at any precise location of the given virtual objects, color matching requires close attention to exact areas of the color-picking widget. We believe that since our experiment employed a virtual widget borrowed from an established VE application, we were able to identify performance differences from other previous studies. Thus, we recommend that future work in display-interaction offset studies explore other elements of deployed VE applications in order that a more complete understanding of offset effect across the taxonomy of interaction techniques be established.

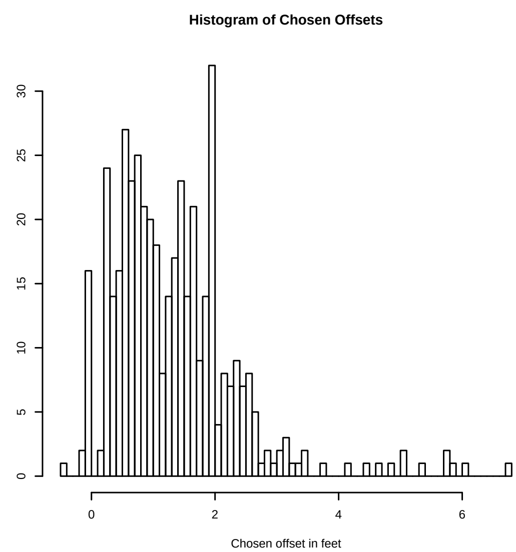


Figure 7: Chosen offsets in the widget placement task.

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