# Visual Transitions around Tabletops in Mixed Reality: Study on a Visual Acquisition Task between Vertical Virtual Displays and Horizontal Tabletops

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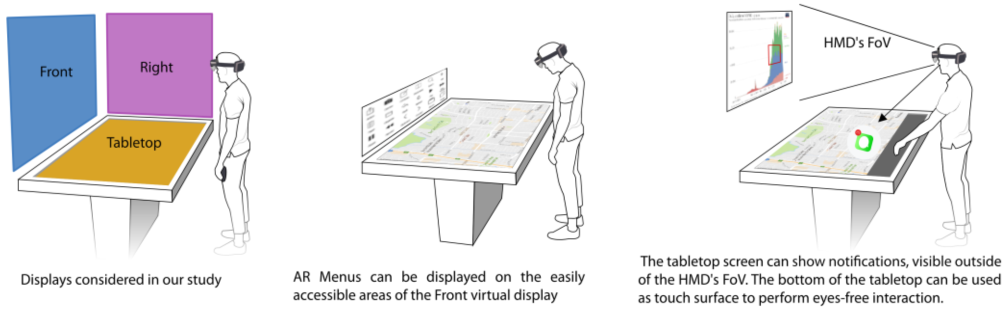


Figure 1. We studied the visual transitions between a horizontal tabletop display and two vertical virtual displays (Front and Right). From this study, we propose a set of guidelines to inform the design of interactive environments combining a tabletop display surrounded by vertical virtual displays using see-through HMDs, as illustrated between the tabletop and the Front displays in the center and right images.

See-through Head-Mounted Displays (HMDs) offer interesting opportunities to augment the interaction space around screens, especially around horizontal tabletops. In such context, HMDs can display surrounding vertical virtual windows to complement the tabletop content with data displayed in close vicinity. However, the effects of such combination on the visual acquisition of targets in the resulting combined display space have scarcely been explored. In this paper we conduct a study to explore visual acquisitions in such contexts, with a specific focus on the analysis of visual transitions between the horizontal tabletop display and the vertical virtual displays (in front and on the side of the tabletop). To further study the possible visual perception of the tabletop content out of the HMD and its impact on visual interaction, we distinguished two solutions for displaying information on the horizontal tabletop: using the see-through HMD to display virtual content over the tabletop surface (virtual overlay), i.e. the content is only visible inside the HMD's FoV, or using the tabletop itself (tabletop screen). 12 participants performed

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visual acquisition tasks involving the horizontal and vertical displays. We measured the time to perform the task, the head movements, the portions of the displays visible in the HMD's field of view, the physical fatigue and the user's preference. Our results show that it is faster to acquire virtual targets in the front display than on the side. Results reveal that the use of the virtual overlay on the tabletop slows down the visual acquisition compared to the use of the tabletop screen, showing that users exploit the visual perception of the tabletop content on the peripheral visual space. We were also able to quantify when and to which extent targets on the tabletop can be acquired without being visible within the HMD's field of view when using the tabletop screen, i.e. by looking under the HMD. These results lead to design recommendations for more efficient, comfortable and integrated interfaces combining tabletop and surrounding vertical virtual displays.

CCS Concepts: • **Human-centered computing → Human computer interaction (HCI) → Interaction paradigms → Mixed / augmented reality**

**Additional Key Words and Phrases:** tabletop, see-through Head-Mounted Display, display combination

**ACM Reference Format:**

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## 1 INTRODUCTION

Large displays allow for a flexible arrangement of content and are therefore recommended for many complex analysis tasks, e.g. large data visualization [1], [32]. Tabletops in particular offer a more natural interaction through multi-touch input and are known to facilitate collaboration [47] as they allow to easily switch between activities such as information search, annotation, accessing data, etc. This is particularly the case in the context of consultation meetings between different actors (politicians, citizens, professional experts) around an urban redevelopment project, a situation we are confronted with in the context of the Urban Development action of the Vilagil project. However, display space is sometimes limited when displaying multiple pieces or layers of information (e.g. a map in crisis management, building information modeling (BIM) data, etc.). In these situations, previous work has considered combining multiple large displays to form display walls [4], which leads to other problems such as the difficult access to distant elements [35] or the lack of display space for private views.

Instead, a promising alternative is to combine see-through Head-Mounted Displays (hereby referred to as HMDs), which offer unlimited display space, with tabletops for their input interaction benefits [40]. In this case, the HMD can render horizontal or vertical virtual displays around the tabletop. However, using horizontal virtual displays would lead to visual distortions. Although Nacenta et al. [34] proposed a way to correct perspective distortion, the overall visibility of such corrected content is limited if distant. Besides, looking at content on horizontal virtual displays on both sides of the tabletop would require larger head rotations than with vertical virtual displays, which could result into discomfort issues [12]. Besides, previous work [29] has established that users tend to align virtual windows with physical landmarks along vertical axes: whiteboards, table edges, etc. Therefore, it is more appropriate to consider the use of vertical virtual displays around the tabletop to display 3D virtual data.

In this context, the foremost question concerns how the combination of the tabletop and the virtual displays impacts the visual acquisition of content: although current HMDs offer a theoretically unlimited display space, to date they have a relatively limited field of view (FoV), which can lead to multiple head movements, increased fatigue or disruptive changes of context. And yet, such limitation is rarely accounted for in previous works combining HMDs and tabletops.

In this paper we thus investigate the impact on visual acquisitions of displaying data with a HMD [5], [8] on virtual vertical displays around the tabletop. To contribute to a better understanding of user's visual interaction in such a combined environment, we investigate three research questions:

1. How much time and effort are required to move one's gaze from the horizontal tabletop to a target on the vertical displays and vice versa (see Figure 1 - left)? To answer this question, we design a task where users have to start looking at one display (either vertical or horizontal) and visually acquire a target on the other display.

2. To what extent the user can simultaneously visually perceive portions of the horizontal and vertical displays? To answer this question, every time the user visually acquires a target we record the portion of the different displays that are visible within the HMD's FoV.

3. Do users visually perceive the tabletop screen in the peripheral visual space (i.e. gaze out of the HMD) and how does it affect target acquisition? To answer this question, we design two conditions for the horizontal display: one where we use the tabletop screen, and another where we use a virtual overlay on the tabletop (using the HMD), i.e. the content is only visible inside the HMD's FoV.

This paper contributes with an experiment exploring these questions. Twelve participants performed a visual acquisition task between the vertical and horizontal displays in our environment. Our results provide a better characterization of the user's interaction capabilities in this combined display space. These results allow us to extract a set of design recommendations for more efficient, comfortable and integrated interfaces combining tabletop and surrounding mixed reality content.

## 2 STATE OF THE ART

Many works have investigated the use of large displays for data visualization [1], [4], [27]. Two major issues are particularly relevant to our work: the layout of virtual displays, and the combination of screens and virtual displays.

### 2.1 Laying Out Virtual Spaces Around the User

The use of a see-through HMDs allows users to visualize information almost anywhere: they just need to direct their gaze towards the display area. The very first works in this domain focused on where to anchor virtual windows [17] : relative to the user, to the physical world or to the HMD. Different studies have been conducted to facilitate information search in this quasi-infinite display space. Ens et al. [13] explored the impact of window size, window tilt and spacing, and the reference frame adopted to anchor the windows. The results show a time saving of 40% when switching between windows arranged around the user, compared to a single fixed view. To support the data mining process, Hayatpur et al. [19] proposed DataHop, a system to spatially arrange and easily trace the whole path of a data analysis. In the particular case of hierarchical data, Satriadi et al. [50] considered displaying 3D information layouts in an immersive environment to understand how users take advantage of the physical space around them. Results show that users avoid occlusions and favor situated information, with a central global view surrounded by detailed views oriented towards them. For data analysis, the FIESTA system [26] immerses users in a virtual 3D room where they can freely create and move the data visualizations on the room walls, which serve as a reference for interaction. Luo et al. [29], [30] investigated how users organize documents during brainstorming tasks in augmented reality, in a furnished or unfurnished room. They discovered a tendency to vertically align items along the edges of the available horizontal surfaces (tables, dressers) or directly on relevant vertical surfaces (whiteboard, door, etc.). SnapToReality [39] even implemented an AR system that automatically aligns virtual content on the edges and surfaces of the real world. Other works have studied different solutions to optimize data visualization in immersive environments while the user is in a mobile situation [14], [15] [18] [25], [36]. But these considerations are beyond the scope of our work. Finally, regarding interaction with the surrounding virtual displays, it has been established that flat surfaces favor 3D pointing compared to curved surfaces, and that the way data is anchored to the user's body (location, alignment) influences performance [28], [54], [55].

### 2.2 Combinations of Virtual Displays with Screens

Multiple works combined the virtual displays provided by see-through HMDs with screens, regardless of their size. They are called VESADs (Virtually Extended Screen-Aligned Display) [38].

First, several works have focused on using the virtual displays as a link between physical displays in a large environment. Forerunners, Rekimoto et al. [46] implemented in 1999 a hybrid environment where the different screens and physical objects of interest in a room are linked together and can communicate through augmented reality interfaces projected on all surfaces. Gluey [51] used the same concept but implemented it with a see-through HMD. Cavallo et al. [8] developed a large environment consisting of vertical screens placed 3m away and all around a non-interactive round table: an immersive 3D visualization is displayed above the tabletop in a HMD and users can display additional content about it on the surrounding screens.

Mobile screens, such as smartwatches, have also been combined with virtual displays [56] [49]. For example, Grubert et al. [31] evaluated the combination of a smartwatch with virtual windows for simple tasks, such as searching for an object on a map, or selecting a menu item. They demonstrated better performance than when using the smartwatch alone. Normand et al. [38] compared the use of a smartphone alone, the use of an immersive visualization alone, and a combination of both, and found a clear advantage for the latter in a visual classification task. A recent review documents the possible combinations between smartphones and HMDs [56]. Combining mobile screens with HMDs allow to preserve the pervasive benefits of HMDs and the tactile interaction of mobile screens [21], [23], [38] [43], while compensating for their reduced display space. For example, the space around the smartphone can be used to display menus [38] and charts [43]; the smartphone can also be used as an input controller, either by taking into account its spatial position [21] or as a tactile interactor [23].

Larger screens can also benefit from a combination with virtual displays. For example, Reipschläger et al. [45] augmented a screen wall with a HMD, to keep a strong spatial proximity between virtual and semantically related physical elements. Butscher et al. [6] developed a system to manipulate virtual graphics by giving them a strong spatial dependency with a tabletop to be able to manipulate them with multitouch interactions. Millet et al. [33] proposed a solution to smoothly alternate between the use of a desktop PC and immersive 3D manipulations. Finally, Reipschläger et al. [44] horizontally and vertically extended a small interactive surface to present menus and additional information such as the orthographic views of the 3D model in progress.

### 2.3 Summary and Rationale for our Study

To sum up, on one hand previous studies established that users may benefit from their physical surroundings for reorganizing and anchoring virtual displays: more specifically users tend to align the windows with physical landmarks along vertical axes (e.g. whiteboards, table edges, shelves, etc). Users also tend to prefer a strong spatial proximity between elements presenting a semantic link. It also appears that remote pointing is more efficient on flat surfaces than curved ones. Finally, beyond users' preferences to vertically arrange virtual displays, using horizontal virtual displays would lead to comfort issues due to the ample head rotations required to look at the virtual content on the sides [12]. For these reasons, in this paper we study the use of flat vertical virtual displays placed around a tabletop.

On the other hand, multiple combinations of displays with see-through HMDs have been studied, from large to mobile ones. Among these combinations, the use of 2D vertical virtual displays around a horizontal screen such as a tabletop presents a number of advantages: 1) the horizontal screen offers a fixed spatial referent and a physical delimiter for tactile interactions and, 2) vertical virtual displays allow to extend the display area with additional information without occluding the primary information on the tabletop. While already envisioned [42], such a combination has not been thoroughly studied from a user's interaction point of view.

We therefore chose to virtually extend the edges of the tabletop using vertical flat displays, on the front and on the side of the tabletop. We explored these two display positions as they differ in multiple aspects: first, they have different sizes, as the tabletop edges are longer in front than on the side; and second, displaying data in front of the user leads to less visual distortion and head rotations than on the side, which could affect the overall comfort and acceptance of the technique. We further describe the experimental protocol in the following section.

## 3 EXPERIMENTAL PROTOCOL

The objective of this study is to analyze the user's behavior when visually accessing the different displays of our environment, i.e. a horizontal tabletop and vertical virtual displays. We measure the time, effort and visible portions of each display at the end of a visual transition between the horizontal and vertical displays (or vice-versa).

### 3.1 Factors

We consider four experimental factors defining the conditions: the position of the vertical displays, the tabletop display modality, the direction of the transition and the position of the target word on the target display. We describe these factors below.

***Vertical display position:*** This factor describes the position of the vertical displays rendered using the see-through HMD. We consider two display positions: one perpendicular to the long edge of the tabletop (*Front*) and one perpendicular to the short edge of the tabletop on the right (*Right*). We do not consider the left edge for this study to reduce the number of trials and because the human field of view is symmetrical.

***Tabletop display modality:*** One of the goals of the study is to better understand if users visually perceive the tabletop content out of the HMD's FoV, and if it impacts the target acquisition. The user may be able to watch the screen content using the peripheral vision, while the content of a virtual display can only be perceived inside the HMD' FoV. To study this question, we consider two tabletop display modalities for the tabletop content: either using the tabletop screen itself (namely *Tabletop Screen*) or using the HMD to display virtual content over the tabletop, which is turned off to avoid any brightness issue (namely *Virtual Overlay*), as illustrated in Figure 2-right.

***Direction of the transition:*** To reflect on the real usage of our environment, where the user could look at the tabletop after working on a vertical display (and vice-versa), we distinguish the trials according to the direction of the visual transition between the horizontal tabletop and the vertical displays: *From tabletop,* or *To tabletop.*

*Target position:* To consider a variety of target positions, each display is divided into a 3x3 grid of targets.

### 3.2 Task

The goal of each trial is to observe and characterize a visual transition from the center of a starting display to a predefined position in a target display. The starting display can either be the horizontal tabletop, in which case the target display is one of the two vertical displays (Front or Right), as illustrated in (Figure 2 - left); or a vertical display, in which case the target display is the horizontal tabletop. The participants were asked to perform the task as fast as possible, but above all in a comfortable way.

To perform the task, the user starts by looking at the instructions, displayed at the center of the starting display. These instructions consist of a graphical representation of the environment (hereafter named the map) showing the possible displays and positions of the target (Figure 2 - left). The user presses a clicker to start the trial, which highlights the target on the map. The participant must then visually acquire the target in the target display: the target is a word that the user must read aloud (Figure 2 - left). The trial is successfully completed when the user reads the correct word. The words contained on each cell of the target display are randomly selected on each trial from a list of twenty words. We did not rely on the HMD embedded eye-tracking for target acquisition as we expected users to sometimes acquire tabletop targets out of the HMD's FoV (eye gaze detection is limited to the HMD's FoV). We thus decided that target acquisition would consist on reading the target word aloud, which ensures that the user is really looking at the target.

At the end of the trial, the role of the displays switches, i.e. the target display becomes the starting display. The instructions map appears at the center of the new starting display, allowing the next trial to start in the other direction. Figure 2-left illustrates a trial starting from the horizontal tabletop and ending on the vertical display in front.

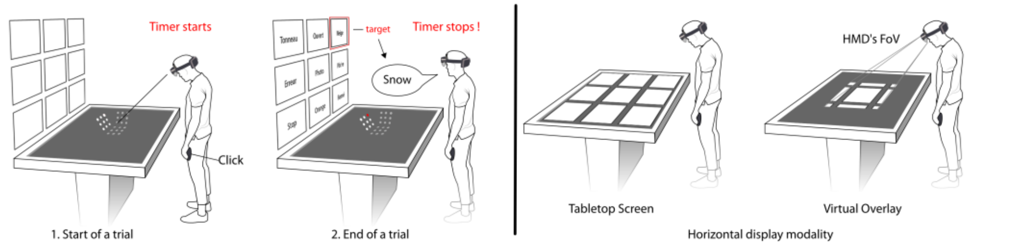


Figure 2. Left: Illustration of a trial starting from the horizontal tabletop and ending on the vertical display in front. Right: To better study the impact of screens and virtual displays, we considered two display modalities for the tabletop: using the tabletop screen itself (namely *Tabletop Screen*) or using the HMD to display virtual content over the tabletop, which was turned off (namely *Virtual Overlay*).

### 3.3 Apparatus

For this study we used a Speechi tabletop (143cm x 80cm, 4096 x 2160 px), a HoloLens 2 HMD (2048 x 1080 (per eye), 52° FoV) and a mouse as a clicker to start the trials (the HoloLens 2 does not have a built-in clicker). The software for both the tabletop and the HMD was developed in C# in Unity. The communication between the two devices was implemented through C# and Universal Windows Platform sockets. We used a PC with an Intel Core i5 processor and 8GB of Ram.

### 3.4 Participants

Twelve male participants aged 20-48 years, with a mean age of 28 years (SD = 7.50), working or studying in computer science, took part in the study. All participants were right-handed and with a right eye dominance, identified using a “hole in the hand test” as described in [48]. All participants had a normal vision and none wore glasses. Two were already familiar with see-through HMDs, one had only tried them once, and the remaining nine had no prior experience with these devices (although a few were familiar with VR HMDs). Only one user had prior experience with a tabletop.

### 3.5 Measures & Collected Data

We collected the time needed to complete each trial. This corresponds to the time between the highlight of the target on the instructions map and the moment when the user starts to pronounce the correct word. This time is retrospectively calculated with the information provided by HoloLens 2: once the word is detected and recognized, Hololens2 indicates the time corresponding to the beginning of the word pronunciation. A trial was tagged as a failure if the spoken word did not correspond to the target word. The HMD had a refresh rate of 60FPS.

We also collected the maximum amplitude of head movements for each trial (in degrees), which was calculated by retrieving the largest angle reached during head movements between the beginning and the end of the trial.

To analyze the surface of each display that was visible within the HoloLens’s FoV at the end of the trial, we overlaid each display with a grid of 10x10 invisible cells. This allowed us to calculate which cell was present within the HMD's FoV and to compute the portion of each display visible in the HMD’s FoV at the time of target acquisition.

Finally, the perceived exertion, i.e. the participant’s evaluation of his/her own physical activity intensity level, was measured through a Borg questionnaire at the end of each block and completed with subjective comments from the participants (semi-structured interview) at the end of the study.

### 3.6 Design

The study followed a 2x2x2x9 within-subjects design, with Tabletop display modality (Virtual overlay, Tabletop screen), Vertical display position (Front, Right), Transition Direction (From Tabletop, To Tabletop) and Target Position (in the 3x3 grid) as factors. The study was divided into four blocks corresponding to the combination of Tabletop display modality and Vertical display position. We counterbalanced these two factors across participants using a Latin square. Each block contained 3 repetitions of the 9 possible Target positions (randomly ordered). Regarding the Transition Direction, participants alternately performed the 2 possible directions (i.e. each trial From Tabletop was followed by a trial To Tabletop). Each block also included training trials. In total, without the training trials, each participant performed 216 experimental trials (2 tabletop display modalities x 2 vertical display modalities x 2 transition directions x 9 target positions x 3 repetitions).

### 3.7 Procedure

After giving informed consent and completing a pre-study demographic questionnaire, the participant put on the HMD and stood in front of the tabletop. The height of the tabletop was adjusted to the height of each participant so that the distance between their head and the tabletop screen was approximately the same. The experiment lasted 35 to 40 minutes for each participant. All equipment was disinfected before each participant to comply with anti-COVID19 guidelines. Participants were asked to remove their masks so not to hinder their lower visual field, but the room was ventilated, and the experimenter kept his mask on at all times.

### 3.8 Data Analysis

We chose to rely on estimation techniques with 95% confidence intervals and within-subjects ratio analysis, as recommended by the APA [11] and following recent conventions in the HCI community (a non-exhaustive list of CHI and VIS studies without p-values can be found in [2]). As discussed in [3], the CHI community strives to emphasize effect sizes and move away from p-values: effect sizes allow for a more nuanced analysis of results, rather than dichotomous inference based on p-values. In this approach, the ratio is a within-subjects measure that expresses the effect size (pairwise comparison) and is calculated between each of the geometric means. All CIs are 95% confidence intervals by BCa bootstrapping, except for the time measures, which were adapted to the T-Test. For the reader more accustomed to interpreting p-values, our results can be read by comparing the spacing of our CIs with the usual spacing of p-values as reported by Krzywinski and Altman [24]. The scripts used to calculate the geometric mean and confidence intervals were used in [53] and are available online [10].

## 4 RESULTS

This section reports the results related to our three research questions, i.e. time and effort required to reach a target, parts of the combined environment effectively perceived by the user, and ability of the user to use its peripheral vision. To this end we analyze target acquisition time, the head movements (maximum amplitude), the content of the HMD's FoV in terms of portions of the displays included in the FoV, and subjective measures including the perceived exertion, preferences, and other free comments. Given the large number of factors of the experiment, we report the more important and relevant measures and analysis for understanding the impacts of combining vertical virtual displays with a horizontal tabletop display on visual target acquisitions with regards to these three research questions.

### 4.1 Analysis of Target Acquisition Times

The following subsections present the average visual acquisition times of the targets according to the Vertical display position first and then to the Tabletop display modality.

#### *4.1.1 Time by Vertical Display Position (Front, Right) and Target Position*

The study of average target acquisition time by Vertical display position reveals longer times on the Right display than on the Front display. Indeed, visual acquisitions from/to the Right took on average 1154ms, [95% CIs: 1096ms, 1216ms] versus 1063ms [95% CIs: 1014ms, 1115ms] from/to the Front (see Figure 3). A within-subjects ratio analysis indicates that the time required from/to the Right display is about 8.5% longer than from/to the Front display (Right/Front ratio: 1.085 [95% CI: 1.047, 1.125]) and this regardless of the direction of the transition (From or To the tabletop).

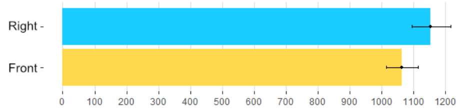


Figure 3. Average trial duration per Vertical display position (Front, Right).

We refined the analysis of the average times for the 9 target positions on each display. Unsurprisingly, the farther the target is from the starting position, the longer it takes to reach it (see heatmaps in Annexes): the target acquisition cost increases along a diagonal path on the Right vertical display (from the bottom left part to the top-right part), and along a vertical path on the Front display (from the bottom to the top).

#### 4.1.2 *Time by Tabletop Display Modality (Tabletop screen, Virtual overlay)*

The analysis of the Tabletop display modality reveals longer average times with a Virtual overlay than with the Tabletop screen. Target acquisitions with a Virtual overlay take an average of 1196ms [95% CIs: 1137ms, 1257ms] versus 1026ms [95% CIs: 971ms, 1085ms] with the Tabletop screen (see Figure 4-left). The analysis of the within-subject ratio clearly confirms this difference: a Virtual overlay induces an acquisition time 16.4% longer than the Tabletop screen (Virtual overlay / Tabletop screen ratio: 1.164 [95% CIs: 1.106, 1.225]). These results are true regardless of the vertical display position (Front, Right) and regardless of the Transition direction (From and To the tabletop). This last result is particularly interesting, given that the Virtual overlay does not display the same information according to the direction: it displays the instructions for transitions *From tabletop*, or the word to read for transitions *To tabletop*.

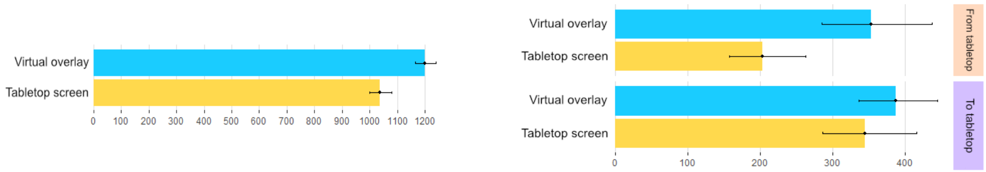


Figure 4. Left: Trial duration (ms) by Tabletop display modality (Virtual overlay, Tabletop screen). Right: Average time before the 2.5° amplitude is achieved (ms) by Tabletop display modality (left axis) and Transition Direction (right axis).

For the transitions *From the tabletop*, we think that the longer trial duration when using a Virtual overlay is probably related to the effort needed to perceive and interpret the trial instruction before starting the head movement towards the target. Indeed, when this instruction is virtual, it disappears from user's sight when initiating the head movement towards the target, given the limited HMD's FoV. We therefore hypothesize that the Tabletop screen allows the user to read the instruction while beginning the head movement towards the target. To confirm this hypothesis, we analyzed head movements over multiple trials, and determined that a movement greater than 2.5 degrees consistently indicated the start of the head movement towards the target. The average time to reach this amplitude is of 203ms [95% CIs: 156ms, 263ms] with a Tabletop screen versus 353ms [95% CIs: 285ms, 437ms] with a Virtual overlay (see Figure 4 - right). The analysis of the within-subjects ratio clearly confirms this hypothesis: the beginning of the head movement towards the target with a Tabletop screen requires about half the time than with a Virtual overlay (Tabletop screen / Virtual overlay ratio, with direction = From tabletop: 0.575 [95% CIs: 0.514, 0.653]).

Conversely, for the transitions *To tabletop,* we performed the same analysis of the time to reach the 2.5 degrees amplitude. Unsurprisingly, as the starting condition does not change (the instruction is always virtual), this time does not clearly differ between the two Tabletop display modalities (large intersection of confidence intervals, Figure 4 - right). This result thus establishes that the observed trial duration difference between Virtual overlay and Tabletop screen, for the transitions *To the tabletop,* is not due to the beginning of the trial on the Vertical display, but rather to the end of the trial on the tabletop, and hence to the Tabletop display modality: the target displayed on the *Tabletop screen* can be acquired faster because the user can see it out of the HMD's FoV.

## 4.2 Maximum Amplitude of Head Movement

In this section, we report the maximum amplitude of the head movement (hereafter referred to as head movement) relative to its orientation at the beginning of the trial. We report this value for each Vertical display position first and Tabletop display modality then.

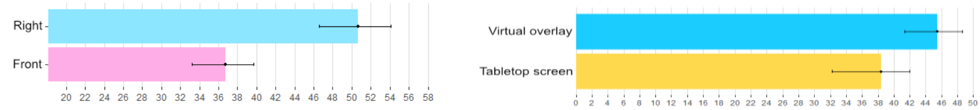


Figure 5. Left: Maximum amplitude of head movement per Vertical display position. Right: Maximum amplitude of head movement (degrees) per Tabletop display modality.

### 4.2.1 *Head Movement by Vertical Display Position (Front, Right)*

An analysis of the maximum amplitude of head movement by Vertical display position reveals a difference between the Front and Right displays, similar to the previous results for the temporal measures: we observed larger head movements for the Right than for the Front display. The Right display induces an average head movement of 50.68° [95% CIs: 46.57°, 54.09°] against 36.73° [95% CIs: 33.19°, 39.72°] for the Front display (see Figure 5 - left). This difference is, interestingly, larger than the one observed in terms of completion time. Based on the intra-subject ratio analysis, the average head movement is 39% greater from/to the Right than from/to the Front (Right/Front ratio: 1.389 [95% CIs: 1.344, 1.445]).

### 4.2.2 *Head Movement by Tabletop Display Modality (Tabletop screen, Virtual overlay)*

The analysis of the maximum amplitude of head movement per Tabletop display modality also reveals some differences. The acquisition of a target on the Tabletop screen requires an average head movement of 38.27° [95% CIs: 32.56°, 41.86°] against 45.71° [95% CIs: 41.54°, 49.14°] on the Virtual overlay (see Figure 5 - right). The within-subjects ratio analysis confirms that head movement is 6% larger with a Virtual overlay than with the Tabletop screen (Virtual overlay / Tabletop screen ratio: 1.063 [95% CIs: 1.037, 1.091]). Full results on the head movement by target position can be found in the Annexes section.

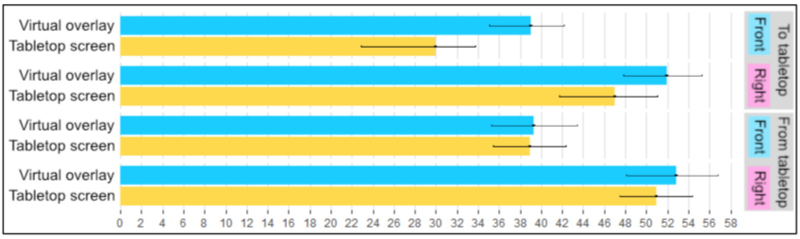


Figure 6. Head movement (degrees) per Tabletop display modality (left axis), Transition direction (right axis) and Vertical display position (Front, Right).

Although this difference is not observed in the direction *From the tabletop*, we found that transition *To tabletop* require a larger head movement amplitude when using virtual overlay (within-subject ratio: 1.647 [95% CIs: 1.184, 3.423] for Front and 1.132 [95% CIs: 1.065, 1.314] for Right). This remains true whatever the Vertical display position (Front/Right; see Figure 6).
To sum up, when starting *From the tabletop*, less time is required with tabletop screen than with virtual overlay because users start the head movement faster (see section 4.1.2). However, in this condition, the same head movements are required as the content to gaze at is virtual and must be seen inside the HMD's FoV. Conversely, when going *To the tabletop*, both time and head movements are smaller with tabletop screen than with virtual overlay. We hypothesize that these

results may be due to the users gazing under the HMD in the tabletop screen condition. To validate this hypothesis, we further analyze the content of the HMD's FoV at the end of the trial.

### 4.3 HMD's FoV at the End of a Visual Acquisition

We now present the measures regarding the visibility of the combined environment during the visual acquisition task. The goals were: 1) to detect if targets displayed on the Tabletop screen were acquired outside of the HMD's FoV (to understand if participants used their peripheral vision); and 2) to measure which portion of the displays was visible within the HMD's FoV at the end of the trial. While these measures depend on the size of the HMD's FoV (HoloLens 2 with a 52° FoV in our experiment), they allow to better understand how the combined environment is perceived and inform the design of interfaces combining tabletop and virtual displays.

We hypothesized that the Tabletop screen would allow participants to visually reach the tabletop target without it being contained in the HMD's FoV (by looking under the HMD for example). To his end, we computed the frequency at which the tabletop target was contained within the HMD's FoV at the end of the trial, for each row of the 3x3 grid of targets.

For the bottom row of targets on the tabletop, the target was in the HMD's FoV in 71.29% [95% CIs: 49.07%, 85.18%] of the trials; for the center row, in 81.48% [95% CIs: 56.48%, 91.66%] of the trials; and for the top row, in 87.96% [95% CIs: 55.55%, 97.22%] of the trials (see Figure 7). These results, along with the maximum amplitude of head movements when transitioning to the tabletop confirm our hypothesis: participant use their peripheral vision to acquire the target outside the HMD's FoV, thus requiring less time and reducing the maximum amplitude of head movements.

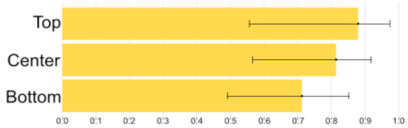


Figure 7. Percentage of target presence in the HMD's FoV at the end of the trial by row in the 3x3 grid of targets when using a Tabletop screen.

By partitioning each display into 10x10 portions and detecting the presence of each portion in the HMD's FoV at the time of the target word reading, we were able to obtain detailed heat maps representing which portions of each display were within the HMD's FoV at the end of each trial. Note that the surface covered by the HMD's FoV is slightly smaller than the one of a Vertical display.

The most interesting results of this analysis concern the acquisition of targets on the Vertical displays: as soon as the user visually acquires targets on the center row of the Front or Right displays, the entire tabletop is already out of the HMD's FoV; however, when a target is on the bottom row of the Front or Right display a large part of the Tabletop display space remains visible in the HMD's FoV, as illustrated on Figure 8.

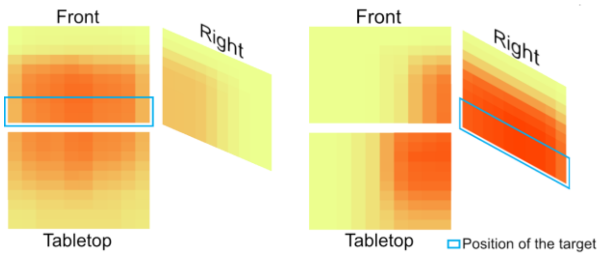


Figure 8. Heat map of HMD's FoV coverage, for: a target on the bottom row of the Front display (left); a target on the bottom row of the Right display (right).

### 4.4 Learning Effect

For all the results presented in the sections above, our analysis did not reveal any clear difference between the three block repetitions. Although the training sessions were relatively short and the participants had little to no introduction to this combined environment, no learning effect could be identified.

### 4.5 Subjective Measures

**Perceived exertion.** The results of the Borg questionnaires reveal a slight difference among the conditions: the estimated effort is smaller for the Tabletop screen (10.99 [95% CIs: 9.62, 12.17]) than for a Virtual overlay (11.42 [95% CIs: 10.21, 12.79]); the estimated effort is also smaller for the Front display (10.88 [95% CIs: 9.63, 12.13]) than for the Right display (11.54 [95% CIs: 10.30, 13]).

In the post-test subjective comments, participants indicated a preference for the Tabletop screen over the Virtual overlay. Participants also felt that target acquisitions from and to the Front display were less tiring than having to turn their heads to the Right display, which correlates with the head movement results and Borg questionnaire results.

Subjective comments collected during the semi-guided interview further confirm this: "I prefer the front, because on the side or down, it hurts..." (P6), or "I had to break my neck to look down to the tabletop..." (P11). Some participants explicitly and positively expressed the fact that with the Tabletop screen they could avoid lowering their head as much as with a Virtual overlay (P2, P7, P9). This correlates with the head movement results where the majority of participants engaged in a different behavior between these two conditions, resulting in clearly smaller head movement with Tabletop screen than with the Virtual overlay (see section 4.2.2).

**User preference.** In terms of preference, 7 out of 12 participants expressed a preference for the Tabletop screen over the Virtual overlay, 3 preferred the Virtual overlay and 2 showed no preference. Participants did not express any additional difficulty in reading items in the vertical displays compared to reading them on the tabletop screen. A few participants did note a difference in colors when displayed with the HMD, however, but added that this did not affect the ease of reading the words.

## 5 DESIGN GUIDELINES FOR INTERFACES COMBINING A TABLETOP AND SEE-THROUGH HMDS

Based on the findings of our experiment, we draw a set of design guidelines for interfaces combining a tabletop and surrounding vertical virtual displays using see-through HMDs. We implemented some of these guidelines and illustrated them in a video provided as part of the auxiliary materials of this paper.

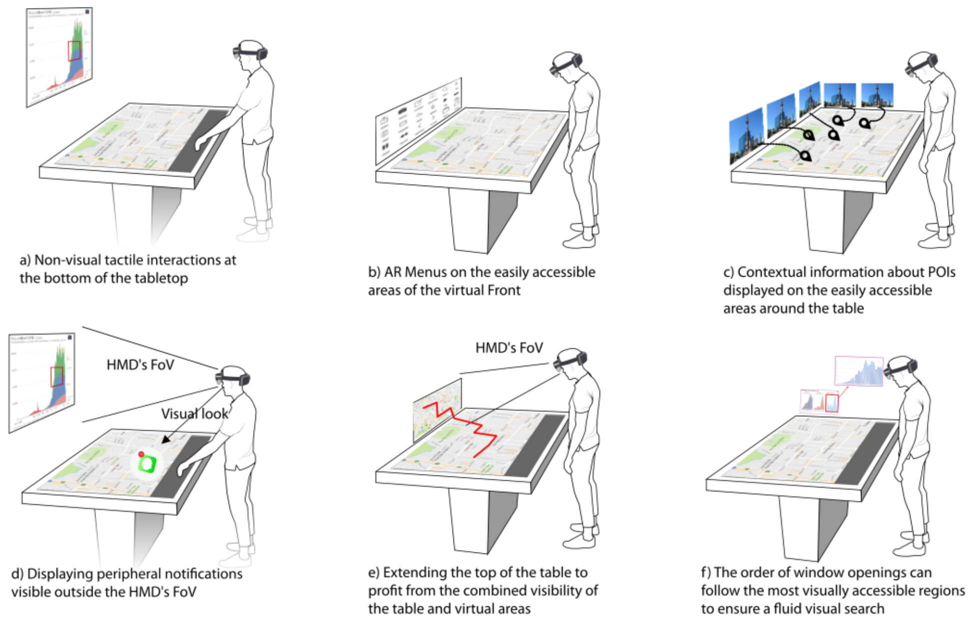


Figure 9. Illustrations of the design guidelines on interfaces combining vertical virtual displays with a tabletop screen.

1) *Best use of display parts according to their ease of access:* Some parts of the displays are longer to reach, such as the edge of the tabletop closest to the user or the upper parts of the vertical virtual displays (see Annexes Figure 10), while others require less time and effort (see Annexes Figure 11). Rethinking the use of these parts could give them novel dedicated purposes. For example, we think that the lower part of the tabletop, close to the user, could be reserved for eyes-free tactile interactions, exploiting for example the principles of MarkPad [22] (see Figure 9-a); the upper parts of the Vertical displays could be used to show only information requiring prolonged attention (see Figure 9-d) while the more accessible parts of the Vertical displays would be more favorable to punctual and brief accesses such as captions, menus, etc. (see Figure 9-b).
2) *Displaying content on the tabletop screen out of the HMD's FoV*: Our results reveal that the tabletop screen targets can be seen outside the HMD's FoV (probably by looking under the HMD, see Figure 7), which probably contributes to the time saving observed to reach a target on the Tabletop screen compared to the Virtual overlay. The tabletop screen can therefore be used in parallel with the Vertical virtual displays, for example to display peripheral information and notifications (see Figure 9-d). Besides, this offers the additional advantage of not requiring the user to lower too much their head, which has been shown to be tiring and uncomfortable.
3) *Displaying content in the HMD's FOV shared across the vertical displays and tabletop screen:* Our heatmaps (cf. Figure 8) show that depending on the position of the target, one or more displays are partially visible at the same time in the HMD's FoV. This allows us to better think about the layout of the virtual content on the vertical displays while taking into account the content displayed on the tabletop. Concretely, for the content on the top part of the tabletop (respectively right), it is best to place contextual information at the bottom of the Front display (respectively bottom-left of the Right display) as illustrated in Figure 9-c. We

can also think of displaying content on the top part of the tabletop while the user looks at the bottom part of the Front display (see Figure 9-e).

4) *Deploying sequential content from the tabletop to the vertical virtual displays:* The heatmaps illustrating acquisition time by target position (see Annexes Figure 10) show that the target acquisition cost follows a diagonal path on the Right vertical display (from the lower left part to the top-right part), and a vertical path on the Front display (from the easier bottom to the top). This information can be used to design sequential openings of related information panels. For instance, selecting a point of interest (POI) on the tabletop could open a first panel on the lower part of the Front display. Selecting an item in this panel would open another panel on top of it (see Figure 9-f).

## 6 LIMITATIONS AND FUTURE WORK

### 6.1 Limitations

While our results provide a better understanding of users' behavior during visual transitions between a tabletop and vertical virtual displays, these results may vary according to the HMD's FoV size. Indeed, the FoV size could have an impact on the users' capability to perceive smaller or larger portions of the virtual displays with more or less head movements. However, the use of the HoloLens 2 in our experiment offered a stable and robust tracking device, which can favor the immediate application of our results given the widespread of this device. In addition, our definition of a clear experimental protocol also favors the replicability of our work. In any case, our work presents a first systematic measurement of a set of fundamental aspects useful for understanding the visual acquisition of digital elements in environments combining a tabletop and vertical virtual displays.

A second limitation of our work concerns our user panel, i.e. male computer science experts. Indeed, it is established that male and female behaviors differ when interacting with 3D environments [9]. In particular, a recent extensive study with over 800 participants [52] highlighted a significant difference in terms of reaction time (among other factors) between males and females. It might therefore be relevant to expand this panel so as to include other genders and domains of expertise to extend the validity of our results.

### 6.2 Future Work

Our study explored a target acquisition task, focusing on temporal data and head movement. We would like to generalize the approach and contribute with a time prediction model adapted to different tasks and displays in a way similar to [7]. It would then be appropriate to consider a more ecological task, requiring to search for information in different displays in a less sequential way or by taking into account several positions around the tabletop (on the short edge of the tabletop, on the long edge, with two users, etc.). We would then be able to identify other measures, such as the impact of the complexity or density of information, the organization of data in space, etc.

We would like to extend our work to a multi-user scenario [20][26],[29] to verify if the vertical virtual displays would hinder collaboration, for example by occluding the other users, and conversely if the presence of others around the tabletop would hinder the perception of the vertical displays. One solution to avoid this could be to distort the vertical virtual displays around the other users using layout optimization approaches as recently proposed by Niyazov et al. [37].

Finally, after having applied these results to the design of a visual interface arrangement, we wish to explore the consequences of this combination of tabletop and vertical virtual displays from the point of view of input interaction: it would then be relevant to think about the design of interaction techniques the best suited to select a target in different places of this type of environment. These techniques could take advantage of the less visible areas for input interaction, take advantage of the presence of the tabletop, eventually in combination with a smartphone [41], or take into account the easily visible areas.

## 7 CONCLUSION

In this paper we studied the impact of combining vertical virtual displays rendered using a see-through HMD, with a horizontal tabletop. For this purpose, we conducted a study where participants had to perform a visual target acquisition by starting either from the tabletop or from a vertical virtual display to visually reach a target in the other display. To study if users perceive the tabletop content by looking outside of the HMD FoV and how this impacts target acquisition, we also considered two display modalities for the tabletop: either using the tabletop screen or a virtual overlay. Our results show that it is faster to acquire virtual targets in the Front display than on the Right. The use of the virtual overlay on the tabletop slows down the visual acquisition compared to the use of the tabletop screen. These results are consistent with the observed head movements, which are larger for the Right display than for the Front display, and for a virtual overlay than for the tabletop screen. Our analysis of the HMD's FoV also reveals that targets on the tabletop screen can be acquired without being visible within the HMD's FoV. From these results, we derived a set of design guidelines for interfaces in such an environment and an illustrated these scenarios in a running prototype.

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## APPENDICES

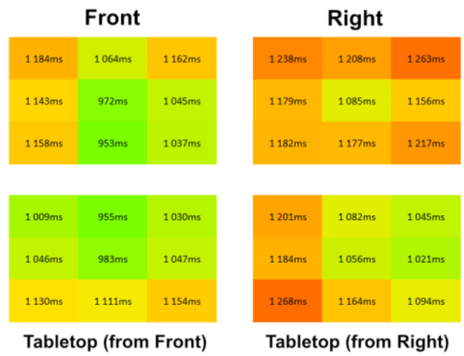


Figure 10. Average trial duration (ms) per display and target position combining both Tabletop display modalities, which reveal similar results regarding the impact of target position.

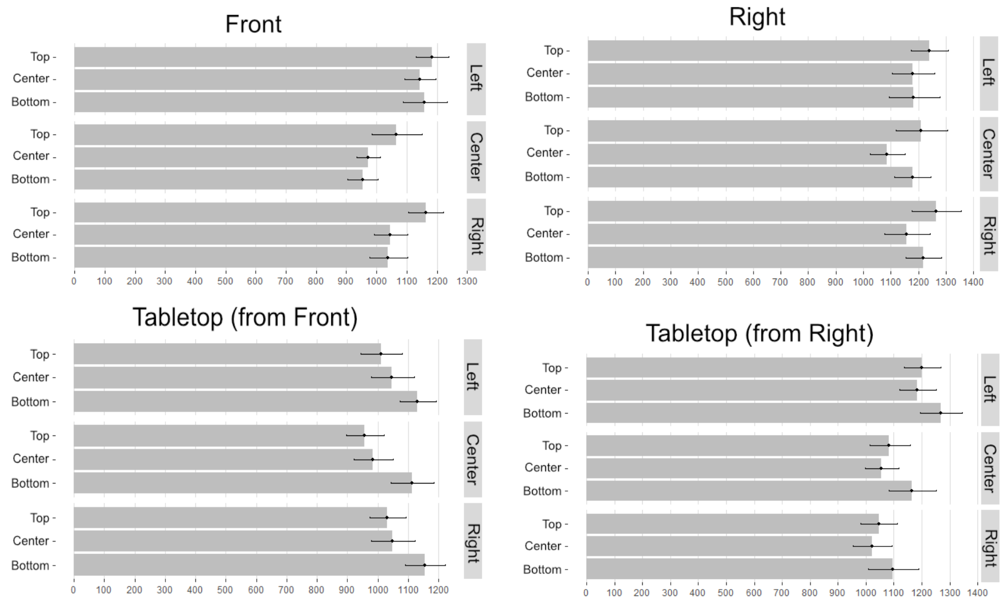


Figure 11. Average trial time (ms) per Display x Row x Column (95% CIs).

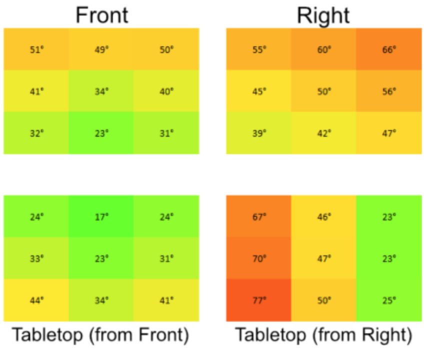


Figure 12. Head movement (degrees) per Tabletop display modality and Target position, combining both Tabletop display modalities, which reveal similar results regarding the impact of target position.

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