What does the Oscilloscope Say?: Comparing the Efficiency of In-Situ Visualisations during Circuit Analysis

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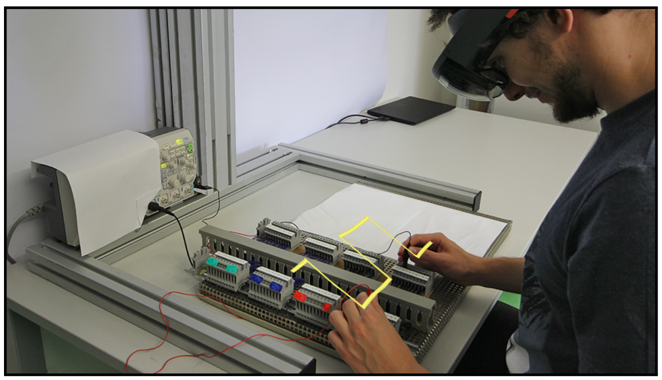

Figure 1: User verifying a circuit with an in-situ visualisation provided by an HMD.

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Abstract

Traditional measuring devices separate probes from their data visualisation, requiring the operator to switch attention between their metering and result frequently. We explored the efficiency of four different *visualisation modalities* during a circuit analysis task that utilises the output of an oscilloscope. We argue that the spatial alignment of an oscilloscope's display and probe interferes with the cognitive processing of data visualisations, hence increasing the probability of errors and required time. We compared a fixed placed *oscilloscope*, *in-situ projections*, *user positioned tablets*, and *head-mounted display* while measuring completion times, subjective workload, number of errors, and personal preferences after each task. Results indicate that the *oscilloscope* produced the lowest completion time compared to other modalities. However, visualising data on a *user positioned tablet* or through *in-situ projections* yielded lower subjective workload and a lower number of errors. We discuss how our work generalises for assistive systems that support practitioners during their training in circuit analysis.

Author Keywords

Augmented Reality; Head-Mounted Display; Projection; Tablet; Oscilloscope; Augmenting Devices

CCS Concepts

•**Human-centered computing** → **Human computer interaction (HCI); User studies; Visualization;** *Mixed / augmented reality;*

Introduction and Background

Technical work and educational areas require to understand abstract concepts that often involve measurements using probes. These tools are considered an integral part of the record and interpret data, for both, scientific and industrial fields. Deviations in data recording or interpretation have detrimental effects on the intended outcome. This effect is amplified when information is viewed and processed in real-time [2, 5], especially when the separation between probe and measurement tool increase the physical activity (e.g., head movements) and increase the working memory demand (e.g., memorising measurement values). Both aspects may contribute to visual strains and a larger error rate. Recently, Augmented Reality (AR) has been employed to deal with these challenges.

Several research projects have investigated the use of projections, tablets, and Head-Mounted Displays (HMDs) influence the overall information processing performance. Funk et al. [3] compared the three aforementioned visualisation modalities, including paper instructions, regarding their performance in a manual assembly task. They found that paper and projected in-situ instructions were faster and more accurate compared to tablets and HMDs. Blattgerste et al. [1] displayed the assembly instructions spatially on the worktable instead of a fixed position. The results show that paper and projected in-situ instructions as provided the best efficiency. Similarly, Tang et al. [11] tested the effectiveness of AR instructions in an assembly task. They compared three in-situ displays: a printed manual, a monitor-based display, and HMD-based instructions. They conclude that HMD-based instructions lowered the error rate while the mental effort decreased for the AR system. Later, Kosch et al. [9] inquired if projected in-situ projections lower cognitive workload compared to paper instructions. Their findings show that the use of projected in-situ instructions lowers cognitive workload on a physiological level. A potential reason why HMDs were less preferred is the continuous visual accommodation between the real-world and virtual artefacts in space. This results in a loss of time where eyes have to focus on real-world and virtual objects [8]. Hence, several studies were conducted to explore a given problem in industrial settings and perspectives. Gabbard et al. [4] conducted a study that explored the costs and consequences of context-switching between real-real and AR-real displayed information. They found less tiredness among participants when the information was presented in the real-real control condition compared to the AR-real treatment condition. Furthermore, participants accomplished a greater number of subtasks in the real-real scenario compared to the AR-real.

In this work, we investigate how different AR visualisation modalities influence the interpretation performance and perceived cognitive workload of a measurement task. We conducted a user study (N=20) to understand how *user positioned tablets*, *in-situ projections*, and *HMDs* perform in terms of user performance and perceived workload compared to an *oscilloscope* during a circuit analysis task (see Figure 1). We find that the visualisation on the *oscilloscope* has the lowest task completion time, whereas *in-situ projections* and *user positioned tablets* require the lowest cognitive effort while making the least amount of errors. Based on our results, we discuss how our findings contribute to the visual optimisation of analysis tasks and outline how practitioners, as well as researchers, benefit from our findings for future research.

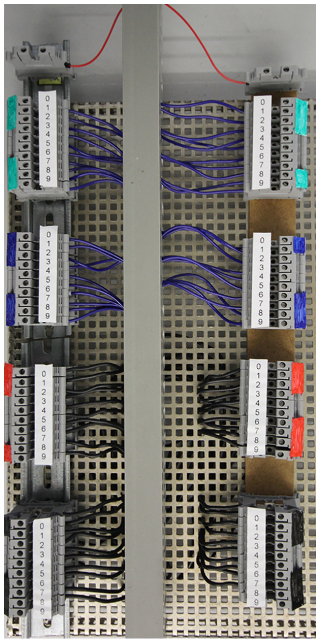


Figure 2: Wiring task used in the experiment. Ten connections were evaluated with each *Visualisation Modality* resulting in a total number of forty connections. Each circuit block had a randomised distinct connection with the opposite circuit block.

System Setup

The experiment employs a wiring task in which participants have to find matching connections using oscillatory measures. We use an *oscilloscope*, *in-situ projections*, a *user positioned tablet*, and an *HMD* to display an oscillatory stream.

The displayed data stream was similar on all *Visualisation Modalities*. Hence, the same data presentation as on the oscilloscope was used for all *Visualisation Modalities*. We elaborate on the wiring task and the *Visualisation Modalities* in the following.

Wiring Task

The setup consists of four sets of connections mounted on a checkboard. Each set consists of ten connections which have a randomised distinct connection to each other (see Figure 2). Participants were asked to investigate the connection between two endpoints of each wire. Participants used the probes from an oscilloscope to assess whether or whether not a connection was established between the endpoints. If an existing connection between both endpoints was measured, a rectangular signal becomes visible via the currently used *Visualisation Modality*. A flat line was displayed when no connection existed. Before starting the experiment, the circuit was placed at the front of the participant. All *Visualisation Modalities* except the currently used one were covered or turned off.

Oscilloscope

We use a RIGOL DS 1054 oscilloscope[1] with a seven-inch built-in display. We consider the oscilloscope as the baseline since it is frequently employed for electrical circuit analysis. The oscilloscope provides two probes that can be used to investigate the connectivity between two endpoints. The resulting signal needs to be visually assessed for existing connections or anomalies in the current flow. During the experiment, the oscilloscope was placed at a fixed position to the upper left from the participant's view (see Figure 3a).

In-Situ Projection

Using a similar setup of Funk et al. [3], a projector mounted above the working area was used to display the oscillatory stream onto the checkboard. We use an Acer K335 DLP projector with a native resolution of 1280px $\times$ 800px and a brightness of 1000 Lumen. The visualisation was projected on a dedicated space on the right side of the participant. The overall projected area was 420mm $\times$ 297mm (see Figure 3b).

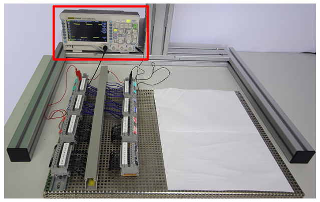
User Positioned Tablets

We use a Samsung Galaxy Tab A6 with a screen size of 10.1 inches as a display that can be placed individually by the user. Data from the oscilloscope was sent to the tablet through a WiFi connection. The user was allowed to put the tablet at a position of their choice (see Figure 3c). However, most of the participants put the tablet on the same spot were *in-situ projections* would have been displayed.

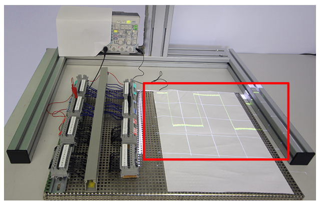
Head-Mounted Display

We use the first generation of Microsoft's HoloLens as an *HMD*. The data visualisation was transferred from the computer to the *HMD* using WiFi. The visualisation was following the user's head and remained at the same field of view and viewing distance. The graph was positioned in the center and was scaled to fully fit the user's field of view (see Figure 3d). No background colour was employed to enable a view-through experience where the oscillatory stream and the checkboard were visible.

[1] www.rigol.eu/products/digital-oscilloscopes/1000z - last access 2020-02-12



(a)



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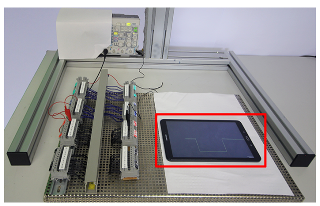
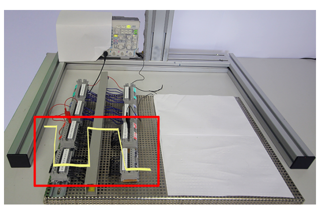


(c)



(d)

Figure 3: Setup of the circuit with four different *Visualisation Modalities*: **(a)** *oscilloscope*, **(b)** *in-situ projection*, **(c)** *user positioned tablet*, and **(d)** *HMD*. The red contour denotes the visualisation.

Experiment Design

We employ a within-subject design with a single independent variable *Visualisation Modality*. Thereby, the independent variable includes the four levels *oscilloscope*, *in-situ projection*, *user positioned tablets*, and *HMD*.

Method and Procedure

The task required participants to discover connections between endpoints in the circuit. After providing their demographic data and written consent, the participants were instructed into the use of probes and assessment of detecting connections in electrical circuits. Afterwards, participants started with the first *Visualisation Modality*. The *Visualisation Modalities* were counterbalanced according to the balanced Latin square. During each condition, participants verbally indicated the end point number when a connection was measured (see Figure 2). Thereby, the participants should state the two matching numbers of an existing connection before moving on to the next connection. An error was counted if the connection mentioned by a participant was not correct. We measure the task completion time between the first and last stated connection for each condition. Participants filled a NASA-TLX questionnaire after each condition to measure their subjectively perceived workload [6, 7]. After the experiment, participants were asked for their personal ranking regarding the four *Visualisation Modalities*. This was accompanied by short semi-structured interviews regarding their self-assessment and perception of the *Visualisation Modalities*. Our participants could rate more than one modality for “the best” or “the worst” condition. Hence, the sums for all displays do not always sum up to 20. The total duration of the experiment was approximately 30 minutes.

Participants

We have recruited 21 participants over university mailing lists (M = 24.48, SD = 2.93, 7 female, 14 male). One participant was removed due to technical difficulties during the experiment, resulting in the data of 20 participants that were used for further analysis. All participants had normal or corrected-to-normal vision. Participants received either 5 Euro or study participation points. Eleven participants had no experience with mixed reality. Five had moderate experienced and four participants identified themselves as experts.

Results

We provide details about the recruited participants and describe our findings. We statistically test our measures for significance using a repeated measures Analysis of Variance (ANOVA). Greenhouse-Geisser corrections are reported when violations of sphericity are detected. We set the alpha level to 0.05 and applied Bonferroni-corrected post hoc tests between the test conditions to investigate the significant main effects of our measures. The averaged results can be found in Table 1.

		Oscilloscope	Projection	Tablet	HMD
Time	M	**92.15**	94.40	97.00	116.40
	SD	**22.99**	26.38	28.58	33.68
NASA-TLX	M	30.70	31.70	**28.25**	40.15
	SD	4.15	4.41	**4.06**	5.21
Errors	M	0.20	**0.10**	**0.10**	0.86
	SD	0.40	**0.30**	**0.30**	1.62

Table 1: Descriptive results of the task completion time, NASA-TLX, and number of errors. Bold values indicate the best results for each measure and condition.

Conditions	p	d
Osc. - Proj.	$.99$	-0.104
Osc. - Tab.	$.99$	-0.169
Osc. - HMD	$.009$	0.827
Proj. - Tab.	$.99$	-0.123
Proj. - HMD	$.079$	0.611
Tab. - HMD	$.128$	0.561

Table 2: Results of the Bonferroni-corrected pairwise post hoc tests for the task completion times. A significant difference was found between *HMD* and *oscilloscope*.

Conditions	p	d
Osc. - Proj.	$.99$	0.127
Osc. - Tab.	$.99$	0.224
Osc. - HMD	$.262$	0.186
Proj. - Tab.	$.99$	0.129
Proj. - HMD	$.17$	0.531
Tab. - HMD	$.296$	0.469

Table 3: Results of the Bonferroni-corrected pairwise post hoc tests for the number of errors. No significant difference was found between the conditions.

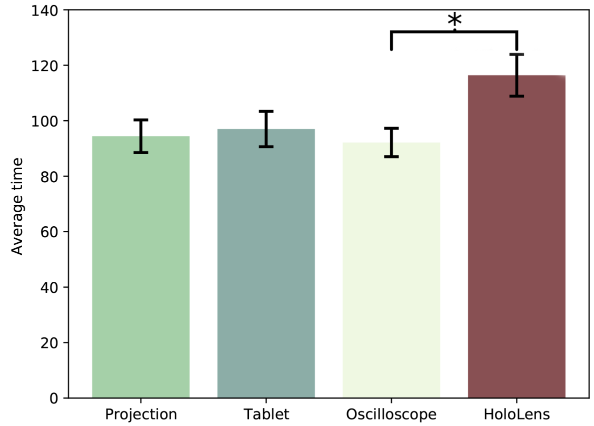


Figure 4: Task completion times for each *Visualisation Modality*. On average, the oscilloscope required the least task completion time compared to the other modalities. The error bars depict the standard error. Brackets indicate significant differences.

Task Completion Time
We find a significant main effect between task completion times for the different *Visualisation Modalities* ($F(2.2, 41.71) = 5.83$, $p = .005$). A post hoc test reveals a significant effect between *HMD* and *oscilloscope* ($p = .009, d = 0.83$). No significant effect was found for the other comparisons. Figure 4 shows the averaged task completion times for each *Visualisation Modality*. Table 2 shows the statistical results of the pairwise comparisons.

NASA-TLX
An ANOVA reveals a significant main effect for the subjectively perceived self-assessments ($F(2.03, 38.52) = 6.282$, $p = .004$). Post hoc tests reveal a significant difference between *HMD* and *user positioned tablets* ($p = .003$). No significant differences between the other *Visualisation Modalities* were found. We further investigate the single scales of the NASA-TLX questionnaire to estimate the critical factors that are manipulated by the *Visualisation Modalities*. An ANOVA reveals a significant main effect in the scales mental demand, physical demand, performance, effort, and frustration ($p < .05$). Applying post hoc tests on the scales reveals significant differences for mental demand between *HMD* and user positioned tablets ($p = .049$, $d = 0.662$), physical demand for *HMD* and *user positioned tablet* ($p = .044$, $d = 0.672$), effort for *HMD* and *oscilloscope* ($p = .049$, $d = 0.660$), and frustration for *HMD* and *oscilloscope* ($p = .024$, $d = 0.733$) as well as *HMD* and *user positioned tablet* ($p = .003$, $d = 0.953$). Other comparisons did not result in a significant difference ($p > .05$). Figure 5 shows the mean raw NASA-TLX scores.

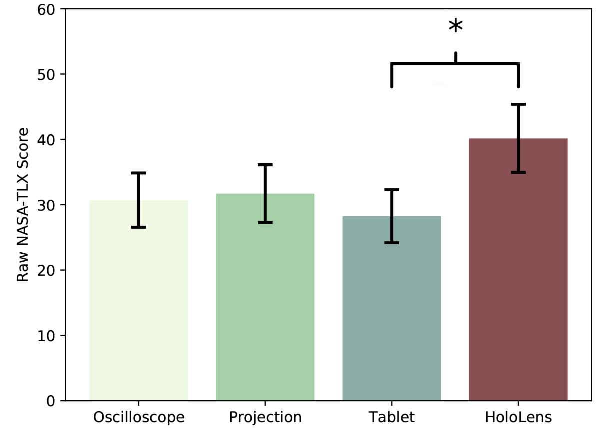


Figure 5: Raw NASA-TLX scores for each modality. The user positioned tablet elicited the least workload compared to the other modalities. The error bars depict the standard error. Brackets indicate significant differences.

	1st	*2nd*	*3rd*	*4th*
Osc.	5	6	7	2
Proj.	4	6	3	7
Tab.	12	1	5	2
HMD	4	2	4	10

Table 4: Personal ranking of the *Visualisation Modalities* oscilloscope (Osc.), in-situ projection (Proj.), user positioned tablet (Tab.), and HMD. User positioned tablets were the most preferred *Visualisation Modality*.

Number of Errors
Applying a statistical test on the number of errors resulted in a statistical main ($F(1.12, 21.30) = 4.617, p = .04$). A post hoc test did not reveal any significant differences between the *Visualisation Modalities* ($p > .05$). The mean number of errors per *Visualisation Modality* can be found in Table 1. Table 3 shows the statistical results of the pairwise comparisons.

Personal Preferences and Qualitative Results
After the experiment, participants were asked regarding their preferred *Visualisation Modality*. They were allowed to choose more that one *Visualisation Modality* as the best or the worst option (see Table 4). Most participants preferred *user positioned tablets* compared to the other *Visualisation Modalities*. Short interviews revealed that the participants endorsed the flexibility of the tablet since "*[...] it can be placed everywhere. The projector would also be good if there is a control for the projected place*" (P4). Others complained that the "*HoloLens was annoying [...]*" (P9) and "*[...] heavy to wear*" (P19). Two participants complained about additional visual stress when focusing on the visualisation, confirming already stated HMD-related issues [8]. They mentioned that "*Switching focus on the HoloLens is demanding*" (P1) and that "*[...] the HoloLens blurs the background and constricts the performing task*" (P18). It is interesting to note that the concerns regarding the visual stress were similar across novice and expert users.

Discussion

Our results imply a trade-off between task completion time and perceived workload. While *oscilloscopes* provide the least task completion time, *user positioned tablets* were deemed more efficient towards workload. A closer inspection of the NASA-TLX scales revealed lower scores in mental and physical demand, effort, and frustration for *user positioned tablets* compared to *HMDs*. Our results suggest the use of separated probes and visualisations (i.e., *oscilloscope*) if time is a critical factor. Otherwise, *user positioned tablets* can be used to optimise workload. On the contrary, the *HMD* elicited the worst performance among the measures. Participants stated repeatedly that visual strains occurred when focusing between task and visualisation. Such a vergence-accommodation conflict requires more research in the domain of usable *HMDs* [10]. This contradicts our assumption that the positioning of the oscillatory stream into the users' field of view was optimal. This was confirmed by the qualitative inquiries, where participants favoured *in-situ projections* and *user positioned tablets*. Hence, future research regarding novel *Visualisation Modalities* should consider the integration of visual feedback into the workplace to avoid strains during a visual signal inspection.

Conclusion and Future Work

In this work, we evaluated four different *Visualisation Modalities* to investigate the efficiency of visualisations that are usually separated from their probes. We compare task completion time, subjective workload, and the number of errors during a wiring task to measure oscillatory streams between wired connections. We find that the *oscilloscope* saves time while *user positioned tablets* provide the lowest workload. We discuss how future designs for data visualisation can utilise our results in terms of time-savings and perceived workload. We conclude that more research is necessary to address visual conflicts that occurred during the use of *HMDs*. To elaborate on this, we will follow up with research that investigates design guidelines for visualisation that minimise the vergence-accommodation conflict during the use of *HMD*. We believe that our research paves for the deployment of assistive technologies that improve the usability and efficiency of tasks that require visual inspection.

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