In-Car Office: Can HMD-Based AR Alleviate Passenger Motion Sickness?

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ABSTRACT

Performing non-driving-related tasks as car passenger reduces visual perception of surroundings, which may cause a conflict with the human vestibular system and thus lead to motion sickness. Augmented reality head-mounted displays offer a possible solution to this phenomenon by presenting digital content at head level as opposed to common displays placed on one's lap, keeping the peripheral vision intact. However, technical limitations such as end-to-end latency of video see-through devices may counteract this advantage. Therefore, we investigated a mobile office scenario by comparing video see-through augmented reality to a traditional laptop setup with regard to motion sickness and task performance in a moving car. Our results suggest similar responses to motion sickness between conditions, with limited effects on task performance and improved ergonomics when using augmented reality.

CCS CONCEPTS

• **Human-centered computing → Mixed / augmented reality**; **Empirical studies in HCI**; • **Applied computing → Consumer health**; **Transportation**.

KEYWORDS

motion sickness, in-car, mixed reality, augmented reality, automotive, office, work environment, human factors

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1 INTRODUCTION

Advances regarding autonomous driving are opening up new opportunities for passengers to use time previously blocked for driving to perform non-driving-related tasks (NDRTs). While this can lead to a decline of visual motion perception and therefore increase the experience of motion sickness (MS) [7], passengers expect a positive impact on work-life balance as commute time could be used for work-related tasks [21]. Here, MS could impair cognitive, physical, physical-visual, and physical-cognitive performance varying across individuals [7, 27]. Current research concerning the usage of in-car augmented reality (AR) and virtual reality (VR) head-mounted displays (HMDs) in the automotive industry [1, 2, 10, 12, 14] could provide a solution by presenting content at head level, while keeping car motion visible in the field of view (FoV).

The exact cause of MS is unclear, with sensory conflict being the leading theory [7]. Regarding passenger movement, MS can also be referred to as carsickness and denotes a mismatch between the vestibular system's perception of self-movement and the static visual impressions. Symptom intensity varies across individuals, with possible aspects of influence being age and gender, among others [7]. Multiple studies which investigated MS in VR in a moving car [4, 16, 20, 22] reported reduction of MS by providing congruent visual motion cues [4, 16, 22]. While McGill et al. [22] stated that mitigation methods cannot be generalized as user preferences vary, it is identified that motion visualization in the peripheral FoV could be a promising mitigation method for susceptible users, as the human eye's peripheral vision is better at perceiving movements than shapes [23]. This was also observed in a study by Kuiper et al. [18], where a reduced perception of motion in the peripheral FoV caused by differing display positions in a moving car resulted in a significantly higher intensity of MS. Furthermore, using a video see-through (VST) HMD can lead to cybersickness, which can arise due to latency between head movement and its visual representation within the computer-generated scene [19], and has also been identified in VST AR by previous research [9]. A limited amount of studies examined VST HMDs in moving vehicles. Yeo et al. [31] combined live 360° Camera recordings with a VR HMD creating a system similar to VST AR while also assessing MS. Goedicke et al. [13] and Ghiurãu et al. [10] presented technical systems enabling VST usage by a driver, with results of Goedicke et al. [13] indicating issues of VST quality due to dynamic lighting and minor influences on driving performance. To the best of our knowledge, MS in context of mobile work performed by passengers using a VST HMD in a moving car has yet to be investigated in detail.

As described above, arising carsickness is linked to incongruent visuo-vestibular sensory information resulting from missing visual perception of self-motion [7, 18, 23]. Utilizing an AR system that allows for an upright posture of passengers could therefore enable visual perception of self-motion, as vehicle windows and surroundings become visible in the FoV. To investigate the aforementioned solution, we performed a pilot study under real-life driving conditions, evaluating the use of a laptop and a VST AR HMD in the context of mobile work. The occurrence of MS over a defined period as well as related effects on human performance were examined. Additionally, qualitative data regarding user preferences was collected to establish a better understanding of system usage. Thus, we form the main research question: *How does passenger use of video see-through AR for work-related tasks affect MS and its influence on task performance in comparison to a laptop?* Based on related research, we derive two hypotheses:

- **H1**: *AR usage improves visuo-vestibular congruency compared to laptop usage and results in less motion sickness*
- **H2**: *When passengers experience lower motion sickness, they exhibit better task performance*

2 METHODS

2.1 Participants

12 participants took part in the study (1 female, 11 male), aged between 23 and 47 years (*Mdn* = 32). Similar to Jones et al. [17], we excluded people from our recruitment that were affected by either imbalance, heart disease, neurological illnesses, traumatic brain injury, and those who take medications affecting balance or waking state as a safety measure. All participants had prior knowledge and experience with AR and VR HMDs. Nine participants already performed tasks like writing emails, coding, and reading in a moving car. Three participants stated that they always look at the keyboard while typing, eight stated that they only glance at it for special characters while one participant was able to free type.

2.2 Apparatus & Test Environment

Participants took place in the front passenger seat of a midsize estate. 6-Degrees of Freedom (DoF) HMD tracking was implemented using middleware by LP-Research [26]. As HMD, the Varjo XR-3 was chosen due to its high resolution, horizontal FoV of 115°, 90Hz refresh rate, and latency of less than 20ms concerning the VST stream [29]. Seat positioning was standardized to reduce effects of body posture on MS [17], and in similarity to Talsma et al. [28] the air conditioning was set to 20° Celsius to avoid effects on temperature perception, as symptoms like feeling warm or sweating are part of employed MS questionnaires.

Two conditions were investigated: The Laptop-Condition (LTc) consisted of a Lenovo ThinkPad P50 (15.6 inches) and the AR-Condition (ARc) consisted of a Varjo XR-3 in VST mode with an AR-Screen being visible in front of participants (see Figure 1). Based on ergonomic guidelines [30] the AR-Screen was positioned with its upper edge at eye level in a distance of 98cm based on the HMDs mixed reality content focus distance. Perceived size and aspect ratio were based on specifications of the LTc to avoid influences on human performance, as larger monitors can have a positive effect [25]. For input in the ARc, a compact Bluetooth keyboard with an integrated touchpad was used.

The route (see Figure 2) was within a traffic-calmed environment closed to the public and featured diverse road conditions, like a tunnel, a roundabout, inclines, and slopes. Its design should prevent participants from remembering the course to obviate potential MS reduction based on the predictability of movements [18]. To ensure internal validity, we employed a reproducible and uniform driving style across all sessions [24], with preliminary training performed by the driver [17]. A speed limiter ensured a uniform maximum speed of 30 km/h [24]. To validate whether uniform driving style was prevalent, vehicle IMU data was recorded.

Figure 1: In-Car Office (From left to right: AR-Condition, AR-Screen mock-up)

2.3 Measures

Office-Tasks: We defined three tasks to resemble frequently occurring work situations. The Write-Task required participants to transcribe a text within four minutes, with text sections varying per repetition. We evaluated the total number of words entered and the number of incorrectly entered characters based on Damerau-Levenshtein distance with adjacent transpositions. The Memory-Task required participants to memorize a combination of three values within six seconds and afterward to retrieve the correct combination out of twelve presented options. The Math-Task required participants to sum pairs of two random numbers ranging from 10 to 48 in two

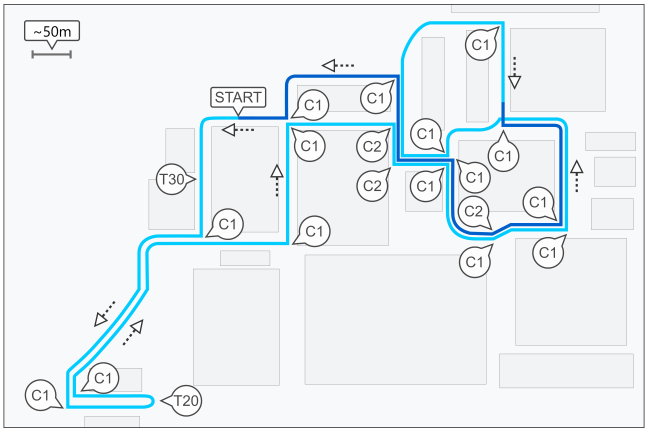

Figure 2: Route and instructions. Legend: T30 (30km/h) represents standard speed, T20 (20km/h), C1 (Car stop before curve / brake sharply), C2 (Slight braking before curve and finishing it without stopping, Colors for better legibility)

minutes by using a visual number pad with mouse input. The number of correct and incorrect entries were recorded for the Memory-Task and the Math-Task.

Cognitive Measures: A paced visual serial addition test (PVSAT) was used to evaluate speed of information processing and working memory [8]. The PVSAT has already been utilized to investigate influences of MS on cognitive performance by Smyth et al. [27]. Participants had to vocalize the sum of two sequentially displayed numbers. To perform the PVSAT, a total of 20 randomized numbers from 1 to 9 were displayed, each was visible for one second with an additional two-second delay in between them. The number of correct answers was measured.

Motion Sickness: We used the misery scale (MISC) [3] to regularly collect data during driving sessions and terminated a session when a value ≥ 6 is reached [6, 18]. Since this caused subsequent measurements to be missing, we employed a method used by Talsma et al. [28] and Kuiper et al. [18], where missing entries were filled up with the last obtained value to compensate for cancellations and used such data for subsequent analysis. This will be referred to as padding and explicitly does not represent values participants might have achieved, had they been exposed to the full 20-minute driving session, as literature suggests continuously rising levels for such a scenario [28]. Therefore, mean values might stagnate at a lower level when padding is employed. For detailed assessment, we employed the motion sickness assessment questionnaire (MSAQ), including gastrointestinal, central, peripheral, and sopite-related dimensions [11].

NASA-TLX: The raw TLX (RTLX) version of the NASA TLX was used to measure perceived task load [15], enabling the analysis of individual sub-scales with their sum being used to calculate the total score.

Qualitative Data: In a semi-structured interview we asked questions related to posture, advantages, and disadvantages of conditions concerning work-related tasks, quality of VST image, environment perception, and preference of conditions. Evaluation was performed by thematic analysis.

2.4 Procedure

A within-subjects design was used, accommodating learning effects by counterbalancing task order. Trials took place on two separate days to avoid habituation effects and to ensure a decay time for any symptoms that might occur [28]. Participants signed a consent form concerning privacy and information sharing, practiced tasks beforehand, were introduced to the questionnaires, and were informed that they could abort the driving session vocally should MS become unbearable. Preexisting experience of VR and AR was collected, with explanations given in case of no prior knowledge. Afterward, the MSAQ (PRE) was collected, followed by the first performance of the PVSAT and a 20-minute long driving session with two repetitions of each office task. Based on balanced latin square, the order of the first three tasks was defined and then repeated.

After one minute, the MISC appeared for the first time, offering a 20-second time frame for completion, with subsequent prompts appearing every two minutes. The driving session was terminated if a MISC ≥ 6 was reached or if participants vocally requested it. Upon completion or termination of the driving session PVSAT, MSAQ (POST), and RTLX were performed, followed by the semi-structured interview.

3 RESULTS

3.1 Influences of Conditions on Motion Sickness

Concerning uniform driving style, analysis of the motion profile was performed using rotational data as well as longitudinal- and lateral acceleration data based on the vehicle IMU. Analysis revealed no significant differences between conditions, indicating internal validity for subsequently presented data. Initial values of the MSAQ (PRE) revealed no significant differences between conditions for total score ($W = 10.5, p = .092, n = 12$) and subcategories, indicating that participants began the study with similar pre-conditions. Opposed to H1, comparing MSAQ (POST-PRE) of both conditions did not show significant differences (see Table 1). However, differences exist in the weighting of individual subcategories of the MSAQ (POST-PRE) across conditions. They can be ordered based on their mean values, thus revealing differing sub-scale rankings:

- LTc: *Gastrointestinal* > *Peripheral* > *Central* > *Sopite*
- ARc: *Gastrointestinal* > *Central* > *Sopite* > *Peripheral*

The gradation order of the ARc is congruent with the one presented by Talsma et al. [28], which is also derived from a measurement of MS while sitting in a moving car.

Similar to MSAQ (POST-PRE), analysis with Wilcoxon signed-rank test did not show significant differences for MISC in comparing conditions by individually highest reached values ($W = 29.5, p = .877, n = 12$), means of individual participants ($W = 34.0, p = .733, n = 12$) and by mean per measurement point in time ($W = 27.5, p = .206, n = 10$). An increased rate of MS progression within the first five minutes (ARc) and seven minutes (LTc) can be observed in figure 3. Since the first MISC measurement of the ARc already contained a higher mean value compared to that of the LTc, while MSAQ (PRE) values indicated similar pre-conditions across participants, faster increase of MS might be attributed to the ARc. Adding to this, participants of the ARc reached a mean MISC of *2.08* after five minutes, while LTc only reached a mean of *1.17*. Four participants reached nausea onset in the ARc (33.4%) and two in the LTc (16.67%), therefore terminating driving sessions. The first driving session termination took place after five minutes in the ARc compared to seven minutes in the LTc, with mean values from there on increasing at a slower pace in both conditions. As mentioned before, this analysis is limited by the employed padding of dropout values. Without dropping out, a further increase of MS scores would have been expected [28].

Within the semi-structured interview, participants mentioned that they perceived vehicle movements primarily by experiencing physical forces during LTc, with almost no visual motion feedback being perceived within the peripheral FoV. Contrary to this, they perceived visual movement cues in the FoV and in part also were able to recognize pedestrians and other cars during ARc. This is probably due to positioning the AR-Screen in front of the windshield, which did not occupy the complete FoV. Furthermore, latency of VST was reported as problematic by two participants, resulting in a negative impact on well-being.

Table 1: MSAQ (POST-PRE) (TS = Total Score, G = Gastrointestinal, C = Central, P = Peripheral, SR = Sopite-related)

Scale	ARc(*M±SD*)	LTc(*M±SD*)	Wilcoxon signed-rank
TS	12.21 ± 10.67	8.39 ± 6.23	$W = 24.0, p = .255, n = 12$
G	16.9 ± 18.67	9.95 ± 9.73	$W = 17.5, p = .182, n = 12$
C	11.11 ± 10.38	7.96 ± 10.09	$W = 19.0, p = .230, n = 12$
P	9.57 ± 14.08	8.95 ± 13.9	$W = 20.0, p = .811, n = 12$
SR	10.88 ± 7.25	6.94 ± 7.35	$W = 16.5, p = .154, n = 12$

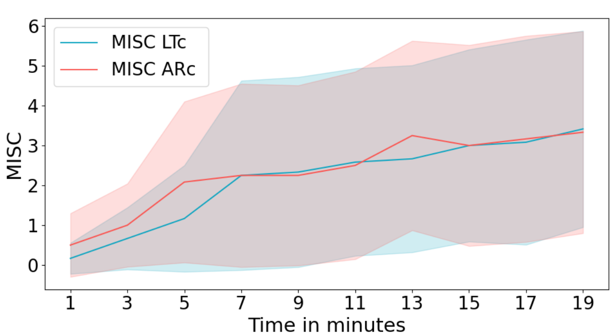

Figure 3: MISC Mean & SD over Time (Padded)

3.2 Influences of Motion Sickness on Human Performance

The Shapiro-Wilk test of PVSAT measurements deviated significantly from normality for ARc ($W = 0.818, p = .015$) and LTc ($W = 0.768, p = .004$), which is why the Wilcoxon signed-rank test was used. Opposed to H2, comparing both measurements taken within each condition revealed no significant differences for ARc ($W = 14, p = .484, n = 12$) and LTc ($W = 4, p = .073, n = 12$). Average scores between the first and second PVSAT execution decreased slightly within the ARc (Difference = -0.166), while LTc contained a value improvement of 0.416 correct answers.

Evaluation of Office-Task metrics was performed in relation to obtained MISC values by using Spearman correlation, with two metrics revealing a possible impact of MS on task performance. Analyzing the number of words entered in the Write-Task of the LTc resulted in a negative correlation with MS and a degradation in performance with a large effect size according to Cohen [5] ($r_s = -0.592, p = .043, n = 12$). Also regarding the Write-Task, incorrect inputs in the ARc resulted in a small effect size according to Cohen ($r_s = 0.199, p = .535, n = 12$), indicating a slight decrease in typing accuracy with increasing MS. Unexpectedly, Word-Count of ARc improved with increasing MS and resulted in a medium effect size according to Cohen ($r_s = 0.438, p = .154, n = 12$), even though participants highlighted problems like the necessity of having to look down at the keyboard in instances as well as issues with its legibility. Analysis of other Office-Task metrics did not result in degraded performance but rather showed improved values with increasing MISC.

3.3 Work environment

Analyzing subcategories of RTLX using Wilcoxon signed-rank test did not reveal significant differences, but suggested a tendency for the sub-scales effort ($W = 18.0, p = .107, n = 12$), frustration ($W = 14.0, p = .099, n = 12$) and total score ($W = 15.0, p = .064, n = 12$) in favor of the LTc. Results of effort, which aimed to elicit workload related to keyboard and touchpad input, were consistent with participants highlighting a lack of precision in touchpad usage. Vehicle movements hindered interaction with content, as the influence of acceleration forces could not be compensated for. Additionally, the touchpad exhibited perceivable input latency in the ARc, whose origin is assumed to be a Bluetooth connectivity issue. This combination of influences affected the selection of small-scaled buttons, like those present in the Math-Task. Shapiro-Wilk test of correct entries in the Math-Task departed significantly from normality ($W = 0.879, p = .037$), which is why Wilcoxon signed-rank test was used, showing a significant difference between the ARc and LTc ($W = 136.0, p < .001, n = 16$), with more entries being made on average in the latter (ARc: $M = 12.69, SD = 4.85$; LTc: $M = 17.69, SD = 4.25$). The associated metric of incorrect answers did not reveal significant differences ($W = 3.0, p = .233, n = 16$). In comparison, the Memory-Task featured large buttons and did not reveal significant differences using paired samples t-test concerning number of correct ($t = 2.043, p = .059, n = 16$) and incorrect ($t = 0.921, p = .371, n = 16$) entries. As such, it can be assumed that more time was required to perform selections in the Math-Task of the ARc due to input latency of the touchpad.

The ability to quickly switch gaze between keyboard and screen due to them being constantly in the FoV was highlighted as positive concerning the LTc. This was not possible in the ARc, thus the necessity to look down at the keyboard was emphasized as problematic by participants who were not able to free type. In return, AR-Screen positioning in the ARc resulted in an upright sitting posture and was positively highlighted by a majority (7 participants) compared to the LTc (3 participants). LTc primarily resulted in a stooped posture, which was identified as a trigger for neck pain. Differences in keyboard usage resulted in significant differences regarding word count ($t = 5.207, p < .001, n = 12$), with improved performance in the LTc ($M = 98.75, SD = 32.35$) compared to ARc ($M = 65.33, SD = 24.06$). Error rate did not reveal significant differences ($t = -1.545, p = .151, n = 12$). Legibility of key labels in the ARc proved challenging, especially in dark environments. Furthermore, free typing was also made more difficult by the compactness of the ARc keyboard.

Regarding subjective system preferences in the context of mobile work, five participants preferred the ARc while four preferred the LTc. Two participants could not decide, as they concluded that both systems offered individual advantages. The most common argument made for the ARc was its improved ergonomics, while the most common arguments made for the LTc were advantages in input precision and keyboard usage, leading to more pleasant task processing. The preference of one participant is missing. The majority (11 out of 12 Participants) could imagine performing mobile work using AR in the future, but only for lightweight tasks such as meetings, answering emails, and editing presentations. However, preconditions for this were improvements to weight, form factor, resolution, and latency of to-be-used HMDs.

4 DISCUSSION

Even though we designed our course and driving style to imitate urban conditions by including turn and braking maneuvers, data obtained within our study might not be representative of conditions outside a controlled environment. Although participant statements confirmed visual perception of motion for the ARc, previously established findings which drew a relation between MS mitigation and congruent visuo-vestibular feedback being provided to participants could not be reproduced within our study. Contrary, while measurements of subjective MS did not reveal significant differences, the ARc featured more cancellations than the LTc. Non-significant differences in terms of MISC and MSAQ despite congruent visuo-vestibular feedback in the ARc could therefore stem from influences in relation to cybersickness in form of latency. As described by two participants, latency within the HMDs 6-DoF tracking and VST processing could have had a negative influence on MS, as has already been indicated by related works [9, 19].

4.1 Limitations

Concerning task performance, presumed learning effects despite preceding training of the office tasks might have influenced results. Furthermore, participants with a MISC ≥ 6 were excluded from the office tasks analysis as they featured incomplete data sets. Two outliers were excluded from analysis of the Write-Task, due to user error and technical difficulties with the keyboard. Based on qualitative data, we suspect further influences on the comparison of office tasks to stem from VST quality, differing keyboard sizes, Bluetooth latency, and the necessity for some participants to look at the keyboard. At last, an important limitation is the generalization of MS progression across participants, as our study featured a small participatory group which also included under-representation of female participants. Excluding participants due to technical issues further limited general validity of the analysis between office tasks and MS.

5 CONCLUSION

We conducted a pilot study on motion sickness in a moving vehicle in the context of performing mobile work using a laptop and an VST AR HMD. Evaluated data opposed our hypothesis that the perception of congruent visual feedback in the peripheral FoV as a result of using AR would yield lower MS across participants. Furthermore, AR usage resulted in four terminations as opposed to two under the usage of a laptop. Influences by latency of the tracking system and VST stream are assumed to have negatively influenced MS. Degrading effects of MS on cognitive performance could only be significantly identified for word count in Write-Task of the Laptop-Condition, opposing our second hypothesis. To address issues regarding the validity of our experiment, we aim to expand our dataset by conducting a follow-up study with the objective of reaching gender parity and a larger participatory group. Furthermore, including an optical see-through display could enable a more detailed comparison without latency influences in which visual motion cues stay visible to participants.

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