Understanding Shoulder Surfer Behavior and Attack Patterns Using Virtual Reality

Yasmeen Abdrabou
yasmeen.essam@unibw.de
University of the Bundeswehr Munich
University of Glasgow
United Kingdom

Radiah Rivu
sheikh.rivu@unibw.de
University of the Bundeswehr Munich
Germany

Tarek Ammar
tarek.ammar@campus.lmu.de
LMU Munich
Germany

Jonathan Liebers
jonathan.liebers@uni-due.de
University of Duisburg-Essen
Germany

Alia Saad
alia.saad@uni-due.de
University of Duisburg-Essen
Germany

Carina Liebers
carina.liebers@uni-due.de
University of Duisburg-Essen
Germany

Uwe Gruenefeld
uwe.gruenefeld@uni-due.de
University of Duisburg-Essen
Germany

Pascal Knierim
pascal.knierim@unibw.de
University of the Bundeswehr Munich
Germany

Mohamed Khamis
mohamed.khamis@glasgow.ac.uk
University of Glasgow
United Kingdom

Ville Mäkelä
ville.makela@uwaterloo.ca
University of Waterloo
Canada

Stefan Schneegass
stefan.schneegass@uni-due.de
University of Duisburg-Essen
Germany

Florian Alt
florian.alt@unibw.de
University of the Bundeswehr Munich
Germany

ABSTRACT

In this work, we explore attacker behavior during shoulder surfing. As such behavior is often opportunistic and difficult to observe in real world settings, we leverage the capabilities of virtual reality (VR). We recruited 24 participants and observed their behavior in two virtual waiting scenarios: at a bus stop and in an open office space. In both scenarios, participants shoulder surfed private screens displaying different types of content. From the results we derive an understanding of factors influencing shoulder surfing behavior, reveal common attack patterns, and sketch a behavioral shoulder surfing model. Our work suggests directions for future research on shoulder surfing and can serve as a basis for creating novel approaches to mitigate shoulder surfing.

CCS CONCEPTS

• **Security and privacy → Human and societal aspects of security and privacy**;

KEYWORDS

Shoulder Surfing, User Behavior, Eye Tracking, Virtual Reality

ACM Reference Format:
Yasmeen Abdrabou, Radiah Rivu, Tarek Ammar, Jonathan Liebers, Alia Saad, Carina Liebers, Uwe Gruenefeld, Pascal Knierim, Mohamed Khamis, Ville Mäkelä, Stefan Schneegass, and Florian Alt. 2022. Understanding Shoulder Surfer Behavior and Attack Patterns Using Virtual Reality. In *Proceedings of the 2022 International Conference on Advanced Visual Interfaces (AVI 2022), June 6–10, 2022, Frascati, Rome, Italy*. ACM, New York, NY, USA, 9 pages. https://doi.org/10.1145/3531073.3531106

AVI 2022, June 6–10, 2022, Frascati, Rome, Italy

1 INTRODUCTION

Shoulder surfing is the act of observing the device screen of other people without their permission [12]. It can occur anywhere and at anytime, making it a common threat to users. Shoulder surfing has received considerable attention from the HCI and usable security communities [7, 12, 31, 34]. Shoulder surfing occurs in various situations and it has considerable negative implications on users [12, 19]. At the same time, we are currently missing an in-depth understanding of how attacks happen and what strategies attackers follow in their attempts. Answering these questions will help designers and practitioners create solutions that can counteract shoulder surfing attacks, providing users with better protection.

Shoulder surfing behavior is difficult to investigate in the real world because it frequently occurs in complex scenarios. Furthermore, from an ethical perspective, undertaking such in-the-wild studies is challenging [39]. Researchers attempted to address this in different ways. For example, Eiband et al. *asked people* about their shoulder surfing behavior in an online survey [12]. Marques et al. *collected stories* from people to learn how they feel about unauthorized access to their smartphones [19]. Although such research showed attackers' motivations and provided insights about the contexts in which shoulder surfing happens, it fell short on capturing shoulder surfers' actual behavior. Saad et al. exposed participants to *360-degree videos* of photo-realistic, pre-recorded public transport situations, including passengers whose smartphones could be shoulder surfed [34]. While this allowed researchers to analyze participants' gaze behavior toward various forms of content, the study was hindered because static video environments prevented participants from moving around and positioning themselves freely.

Prior research suggests that Virtual Reality (VR) in combination with eye-tracking is a promising next step toward gaining a more detailed understanding of shoulder surfing. This is also supported by further research demonstrating that VR can serve as a means to observe behavior as it occurs in the real world [2]. Examples include work on public displays [18], gaze behavior [36], and security mechanisms [21], all of which compared results from VR and the real world. We see a particular strength in using VR as it can simulate real-life scenarios while maintaining control over interruptions and unwanted stimuli; it also allows users to navigate freely in the environment, supporting high immersion and presence; and it allows additional behavioral data to be captured and analyzed, such as eye-tracking and data on user position.

As a result, we contribute a VR study on shoulder surfers' behavior. We implemented two waiting situations, which were inspired by a recent survey that identified waiting as one of the most common contexts for shoulder surfing [12]. The two scenarios represent a bus stop and an office workplace in which a variety of avatars interact with different devices. The bus stop is used to explore shoulder surfing behavior towards smartphones, while the office environment is used to investigate shoulder surfing on larger screens (desktops).

Building on our previous work [1], we report on a user study ($N = 24$) where we put participants in the aforementioned settings and recorded their' gaze and position in VR. This allowed us to (1) understand the effects of the victims' gender, screen content, and distance to the victim on attacker behavior, (2) derive an in-depth understanding of common attack patterns, and (3) create the first behavioral model on shoulder surfing, consisting of multiple stages through which attackers transition during the attack.

Contribution Statement. Our contribution is threefold: 1) We introduce VR as a method for investigating shoulder surfers' behavior and demonstrate its utility in a user study; 2) we provide empirical insights on different factors influencing shoulder surfing; and 3) we identify different attack patterns and propose a stage-based behavioral model for shoulder surfing attacks.

2 LITERATURE REVIEW

Our work builds on several strands of prior research, most notably work on shoulder surfing and on virtual research environments.

2.1 Shoulder Surfing

Shoulder surfing has been primarily considered a threat to authentication. Muskhlov et al. found that shoulder surfing is not only a major concern among users, but that a considerable number of users have had a negative experience with unauthorized access to their smartphones as a result of shoulder surfing [23]. Aviv et al. quantified the susceptibility of different authentication mechanisms to shoulder surfing [3], finding that Personal Identification Numbers (PIN) are generally more secure than lock patterns and that longer passwords are generally more secure than shorter ones. Eiband et al. studied what content is being shoulder surfed and what motivates the attackers. They found that credentials are indeed subject to shoulder surfing. Yet, they contributed less than 10% of cases, while text and pictures (mainly from instant messaging and social media) were more frequently shoulder surfed. This is likely because shoulder surfing tends to occur casually and opportunistically [12].

Shoulder surfing has primarily been studied in the context of smartphone use, but other scenarios have also been studied. Brudy et al. looked at shoulder surfing on public interactive displays [9]. Watanabe et al. investigated shoulder surfing in the work context [38]. George et al. investigated shoulder surfing in VR [10].

Researchers have also proposed mitigation strategies. Most notably, researchers have designed approaches to protecting credentials from shoulder surfing, including PINs [15, 16, 27, 37] and textual and graphical passwords [11, 26]. Also Farzand et al. investigated the personal relations and shoulder surfing mitigation strategies [13]. Again, these countermeasures mostly focus on personal mobile devices, but there is also work on mitigation strategies on other devices like public displays [9, 15] and heads-up displays [41]. Strategies for protecting credentials include making input difficult to observe, e.g., by modifying the input cue, using distracting elements (e.g., multiple cursors [38]), and obscuring the input area with the body [9]. Another approach is to make users aware of potential attacks and let them chose the best coping strategy [31].

Summary. Shoulder surfing is a major threat for different types of content. Yet, most mitigation strategies are currently optimized for security and add a substantial burden to users. For example, authentication mechanisms protecting from shoulder surfing usually lead to longer input times. However, as it comes to protecting content beyond credentials, approaches constantly making the interaction more cumbersome to protect from shoulder surfing are unlikely to be accepted by users. With a better understanding of shoulder surfers' behavior, we intend to pave the way for novel mechanisms that protect from shoulder surfing while maintaining high usability.

2.2 Virtual Reality as Research Environment

VR holds a lot of promise to investigate user behavior, especially in situations that are difficult to investigate in the real world. This approach has for decades been used in the automotive industry, where VR driving simulators allow user interfaces to be tested without putting drivers at risk. As HMDs are becoming widely available and accessible and holistic Virtual Reality environments can be created [25], also other research areas consider this approach. VR allows challenging settings to be replicated, and studies could be run remotely with more diverse samples [24]. Also, VR provides researchers with a lot of control over the VR environment, and other users can be simulated, thus reducing the effort to run studies.

Mäkelä et al. observed participant behavior in VR around large displays, using avatars as bystanders [18], and found that many aspects of human behavior in VR are comparable to the real world. Rovira et al. studied intervention behavior in violent emergencies using VR [28, 30]. Sidenmark et al. looked at how humans perform gaze shifts in VR, finding that behavior is comparable to the real world [36]. Mathis et al. [20] used VR to observe how avatar appearance can affect a bystanders interaction identification performance.

Hence, prior work suggests that VR is a promising way to investigate human behavior. We believe this to be particularly promising for situations, such as shoulder surfing, which are difficult to create and observe in the real world. At the same time, VR has not been widely used as a tool in usable security, an example being work comparing authentication in the real world and VR [15, 21].

Saad et al. [34] used 360-degree videos to study shoulder surfing. They used a 360 camera to record staged real-life situations including opportunities for shoulder surfing, and then played those videos out to study participants. This allowed them to understand which content on smartphones attracts shoulder surfers' attention and how two static camera positions influenced this behavior. Our work is different as we investigate factors affecting shoulder surfing in addition to attackers' behavior and attack patterns.

Summary. VR is a promising way to advance our understanding of shoulder surfing. By extending prior work to VR settings in which people can move and look around freely, we also seek to identify attack patterns and to derive a shoulder surfing model.

3 EVALUATION

The objective of our work is to advance our understanding of shoulder surfers' behavior, in particular how they carry out the attack.

3.1 Research Questions

Our work is driven by several research questions. First, to better understand influencing factors on attackers' behavior, we investigate the question: What is the influence of (a) gender, (b) screen content, and (c) distance between attacker and victim on shoulder surfers' behavior? Second, to advance our theoretical understanding of shoulder surfing attacks, we ask: Which different attack patterns exist, and how can we model shoulder surfing behavior?

3.2 Study Design

We conducted a within-subjects design lab study. Each participant experienced two environments (bus stop, open office space), counterbalanced using a Latin Square. The study involved the following *independent variables*: environment (bus stop vs office), avatar gender (male vs. female), and screen content (news article / video vs. chat / email vs. game). The screen content was assigned to one avatar and counter-balanced for every participant and scene. For the bus stop scene, as there were two screens but three types of content, we ensured that each content was shown equally often.

We collected 1) participants' gaze direction (x, y, z), 2) participants' position in the virtual environment, 3) participants' head rotation, 4) Euclidean distance between the participant and the screen, and 5) the object in focus calculated from the gaze hit position as *dependent variables*. We also recorded a video capture of the attacker view, including participant's gaze direction.

3.3 Virtual Environment

Shoulder surfing often occurs as a result of people being bored [12]. Hence, we designed two waiting scenarios. Scenes were chosen to represent open air and indoor environments as we hypothesized users to behave differently depending on the environment.

Bus Stop Scene We implemented a bus stop in a rural scene with a male avatar and a female avatar, both standing and holding a smartphone (Figure 1). The smartphones showed different types of content with which the avatars would interact in different ways: a news article (just reading/observing), a chat application (text typing), and a tennis game (touch interaction). Initially, the participant was placed between both avatars at a distance of approximately 1 meter. As participants looked at or approached one of the avatars, the avatar's behavior followed the following protocol. The avatar would unlock their phone first by entering the PIN '085212' and then begin to engage with the content described above. The scene also included a bus approaching from the distance and a display saying the bus would arrive in 2 minutes. To make the scene realistic, we designed shops and buildings around the bus stop. This way, we intended to elicit natural behavior where participants could decide to explore the environment rather than to shoulder surf the avatars. Furthermore, the avatars occasionally looked to the right and to the left, to simulate observing the approaching bus.

Open Office Scene Secondly, we implemented a scene placed in an open office space, including an area where people could wait for a meeting. Nearby employees could be observed while working (Figure 1). The scene included three avatars, two males and one female. All were sitting and working at a desktop computer, the display of which could show different types of content: watching a soccer game (just watching/observing), email writing (text typing), and playing a Solitaire game (mouse interaction). Initially, a participant would be placed at the room's door, approximately 3 meters away from the avatars. The scene was again designed to be as realistic as possible. The office was situated in a skyscraper, with the outside scenery being visible. The scene included a poster wall, wall paintings, chairs, and desk objects. Again, this was done to allow participants to just explore the environment.

3.4 Apparatus and Participants

To collect users' gaze data, we used the HTC Vive Pro Eye headset with integrated Tobii eye tracker with a resolution of 1440×1600 pixels per eye and at a frame rate of 90 Hz. The headset was attached to an Alienware Core i7 and 16 GB RAM and was developed using Unity. The study was conducted in a lab at our University. The space in which users could move was appr. 2×3 meters in size. During the study, we followed all hygiene protocols at our University.

We recruited 24 participants (15 male, 9 female) through mailing lists and social networks (avg. age 27.25 years, SD = 6.66). Participants had backgrounds in engineering, political science, CS, and administration and rated their VR experience as average (M=2.4) on a 5-Point Likert item (1=unexperienced to 5=very experienced).

3.5 Study Procedure

We first briefed participants about the study. We told them that the objective was to better understand how they perceive day-to-day situations in VR. Participants were naive to the specific research questions. We did not mention our interest in shoulder surfing. Afterwards, we asked participants for consent to collect their data and provided them with a demographics questionnaire. Then, they to put on the HMD and we calibrated the eye tracker. Participants were then put in the first scene. At the bus stop we asked them to

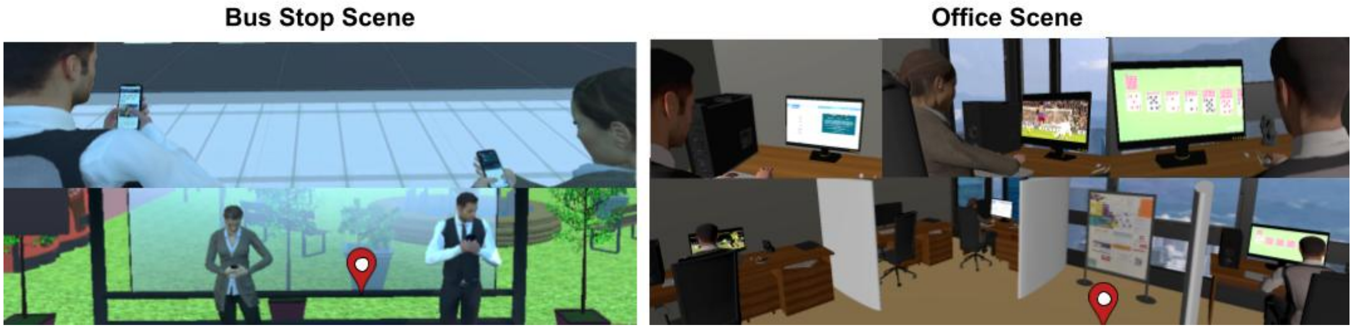

Figure 1: Study Settings: The open office setting (right) included three employees working at desktop computers. In the bus stop setting (left), two passengers interacted with their smartphones. The red markers depict participants' initial position.

wait for the bus. In the office space, we told them that they were waiting for a meeting and that somebody was to pick them up soon. Each scene lasted about two minutes. Once participants finished the tasks, they filled in a presence [40] and a post study questionnaire. At the end, we revealed the true purpose of the study. Each session lasted 30 minutes. Participants were compensated with 5 euros.

3.6 Limitations

We acknowledge the following limitations. First, with the resolution of our VR headset it is still difficult to read small text at a distance. Second, we only investigated two specific scenario in which shoulder surfing occurs. While waiting is among the most frequent situations, future work could investigate additional scenarios.

4 ANALYSIS METHODOLOGY

We identified fixations using the Dispersion-Threshold Identification algorithm, using the default values [35] to remove gaze data noise. Then we used the eye gaze fixations in our analysis to understand where the users were looking in the environments.

To identify the different attack patters, we used the *SPAM* algorithm (*Sequential PAttern Mining* [sic] [4]) which searches for statistically relevant patterns between data samples in a sequence [17]. Our implemented version is based on the users' gaze hit object name. To reduce noise within the data, we first apply a mode filter with a window size of 7 which corresponds to 1/5 second at our sample rate of 35 Hz. Then we clustered all objects into three sets: i) the *attack*-related set contains the shoulder surfed devices such as the smartphones or monitor displays, ii) the *avatar*-related set contains the avatar's body parts and iii) the *other*-related set contains all other objects such as the floor, furniture, walls, etc.

Finally, we apply SPAM to find all possible sequences that contain shoulder surfing attacks, represented in participants' gaze dwelling on an *attack*-related objects. When such an attack is found, SPAM analyzes gaze positions prior and latter to the attack within an interval of 5 seconds. The output yields a set of two-tuples containing the gaze at one of the three sets of virtual objects and the number of frames that the gaze was focused on, such as $((other, 23), (attack, 85), (other, 63))$, where the sequence consists of 23 frames dwelling at *other*, then performing an attack for 85 frames followed by a dwell time of 63 frames at *other*. From this, we clustered these tuple sequences corresponding to three attack patterns, *Continuous*, *Cautious* and *Repeated*.

5 RESULTS

In the following, we report on the study results. We first look at how shoulder surfers behave generally before more specifically assessing different influencing factors. We analyze participants' gaze behavior—as gaze monitoring has shown effectiveness in protecting users' privacy [14]—and their movement in both settings. We then report on the subjective shoulder surfers' view. Finally, we report on how participants perceived the study environment. Unless otherwise stated, data was non-normally distributed (confirmed by Shapiro-Wilk and Anderson-Darling tests) and, hence, we performed non-parametric tests. We report mean values (M).

5.1 Data Overview and Behavior Analysis

Overall we collected an average of 8640 data frames for each participant which corresponds to an overall of 96 minute recordings. To understand if shoulder surfing happened or not, we analyze users' number and duration of eye contact with the avatars' screens.

Number of Eye Contacts with Screens. Participants looked at the screens of the avatars at least once. During the scenes, participants looked at the screens 5.7 times on average. Participants in the *open office scene* looked on average 8.0 times in the two minute time span (between 2 and 25 fixations). Participants looked 3.4 times on average at the *bus stop scene* (between 2 and 22 fixations).

Duration of Eye Contact with Screens. We looked at the participants' eye contact duration on the avatar screens. The average time spent was 1.61 seconds. In the *open office*, we found that participants gazed at the screens on average for 2.1 s (1.16 s — 7.53 s). In the *bus scene*, participants looked for 1.12 s on average (1.01 s — 2.96 s). From this, we consider a shoulder surfing attempt if participant's eye contact with the avatar screen exceed the 1 second.

5.2 Influencing Factors

We investigated the influences of different factors on shoulder surfing: avatar gender, screen content, and distance to the avatar.

5.2.1 Avatar Gender. We assessed if avatar gender had an impact on whether participants shoulder surfed and for how long. We looked at the bus stop scene as gender was equally distributed. We discovered that males (2.37 times) and females (2.43 times) were attacked nearly equally often. We discovered that attacks on female screens persisted roughly 30% longer (18 s) than attacks on male screens (13 s). Using Wilcoxon tests, we found no statistically significant impact of avatar gender on number of attacks and duration. Prior work suggested that females were more often shoulder surfed than males [12]. We can neither confirm nor refute this finding. Prior studies did not reflect on the duration of shoulder surfing attacks for different genders. Our data suggests that females are shoulder surfed longer, but this needs further investigation.

5.2.2 Content. We compared the effects of different screen contents on shoulder surfing. We focused on the open office space for this analysis as all three types of content were visible at the same time. We first looked at the *duration*. Attacks on games lasted the longest (on average 6.6 seconds), followed by videos (6 s), and typing (5.6 s). We also looked at the *number of attacks*. Typing was the most frequently attacked (3.7 times on average), followed by games (3.14) and video (2.4). Using Wilcoxon test, the differences in both situations were not statistically significant ($p > .05$).

From this we learn that text—as it is being typed—seems to be attacked more often but for shorter time spans. The reason might be that attackers repeatedly check back on new text (as reading text is usually faster than typing). In contrast, video and games seem to be attacked less often, but for longer time windows. We come back to this observation when introducing different attack patterns.

5.2.3 Distance and Positioning. We looked at how people positioned themselves in relation to the screens. As a result, we looked at situations when people walked away from their starting position and measured the distance to the screen each time they stopped. In the *bus stop scene*, people positioned themselves approximately 17.6 cm from the screen on average, and 150.8 cm in the *open office scene*. This suggests that participants positioned themselves roughly halfway between their starting location and the avatar's screen in the office. Participants positioned themselves closer to the screen (two-thirds of the distance) as the screen became smaller.

Finally, we looked at how the distance between attackers and displays affected the frequency and duration of attacks. We defined a distance threshold, which is the average distance that attackers positioned themselves at for each scene separately. Attacks where shoulder surfers were further away from the threshold were labeled as 'far,' while others were labeled as 'near'.

In terms of *duration per attack*, we noticed that participants who stood closer to the display had a longer attack duration (18 s vs. 16 s in the open office scene and 16 s vs 15 s in the bus scene). A Wilcoxon test revealed a statistically significant influence of distance on attack duration for both the open office ($Z = -2.16, p.01$) and the bus stop ($Z = -3.23, p.01$). We also looked at whether the distance between the attacker and the screen had an impact on the *number of attacks*. In both the bus scene and in the open office scene, the attacks occurred 2.7 times more when users were close to the screen and 2.4 times more when they were far away. The difference was not statistically significant, according to a Wilcoxon test, $p > .05$.

The aforementioned findings should be interpreted with caution. Participants in several cases moved quite near to the screens. While this may be true in the real world (for example, in a busy subway), it is also possible that participants went closer to better observe text-based content in our scenario (where the environment was not crowded). As a result, while our data suggest that distance does affect attack length, more research is needed to validate this.

5.2.4 Participants' Perception. In our post study questionnaire, we asked participants to rate for each scene how strongly they considered gender, content and distance to influence their shoulder surfing behavior (5-Point Likert scale, 0=very low influence, 5=very high influence). For both scenes, participants felt distance and content to have the strongest influence, as opposed to gender. This finding supports the assumption that shoulder surfing often happens opportunistically (e.g. when people are close) but that at the same time interest (towards the content) also plays a role. People seem to not (at least consciously) be influenced by gender.

5.3 Participants' View & Awareness

Participants filled in a post study questionnaire in which we assessed their personal view and to understand how aware they were of their shoulder surfing behavior. First, we asked participants *which avatar they observed first*. For the open office scene, male and female avatars were mentioned equally often (12). For the bus stop scene, twice as many participants reported having looked at the female avatar first (16) as opposed to the male avatar (8). In particular, male participants attributed the fact that they first looked at female avatars to personal preferences. We also asked about the *general perception* and *thoughts about the scene*. We return to this in the discussion. Here is an example: *[Shoulder Surfing is] alright since usually in a[n] office you can see the other screens. In the office usually people do stuff which are "allowed" to be seen. (P24, m, 28 y)*

When asked retrospectively about *how they felt during and after shoulder surfing*, participants provided mixed answers. Some reported having been curious, while others said they were not interested at all. Some participants reported to have felt ashamed. The latter findings confirm prior work, as shoulder surfers often report negative feelings after shoulder surfing [12].

We also assessed *in how much detail participants could recall* the scene and, in particular, the shoulder surfed content. For the office scene, 54.2% of the participants were able to successfully report the content on all displays, whereas 87.5% of the participants reported details of at least one display. Some mentioned further details, such as football players or clubs names. In the bus scene, only 37.5% of the participants reported successful observations on both avatars' displays, and 66.6% reported detailed descriptions on at least one phone. Differences in the scenes might be explained by the different screen sizes and nature of the settings, as the bus stop was more dynamic with moving cars. Future work might investigate how the shoulder surfing context influences shoulder surfers' ability to recall shoulder surfed information.

5.4 Perception of Study Environment

In the following section, we report on how appropriate our study setting was to obtain a better understanding of shoulder surfing attacks. In particular, we investigate how present participants felt in the environment and how plausible they considered it to be.

5.4.1 Presence. The presence questionnaire was composed of 32 questions, rating the presence using four factors. This 7-point Likert scale measures the subjective feeling of being inside the environment (0=very bad; 6=very good) [40]. Participants rated their perception of presence as follows: Involvement (2.93), Adaptation/Immersion (2.67), Sensory Fidelity (3.43), and Interface Quality

(4.1). The results confirm that the VR situation worked as intended. Users attributed a very good interface quality. At the same time, immersion and involvement were medium as a result of the waiting situation. Due to the observation tasks requiring no interaction from participants, adaptation ratings were rather low.

5.4.2 Plausibility. Several comments in the questionnaire hint at how plausible participants considered our environment. We had implemented the avatars to occasionally look to the right and to the left. This created situations in which participants felt as if they had been caught by a victim in the real world.

To test different types of content, two employees in the office environment performed non-work-related tasks (playing a game, watching a video) – as they might do during a break. This was pointed out by one participant: *[I was] a bit confused (as this was supposed to be a working environment, and only one of them seemed to be working). (P4, f, 27 y)*

From this, we learn that the design of environments to investigate shoulder surfing is not an easy task. People may have different expectations and conceptions towards the environment (as in this case, for some it might be ok to see people do non-work-related things in an office environment but for others it might not). We are interested in seeing which other shoulder surfing environments the scientific community might come up with to add to our initial insights and to further enhance this methodology.

5.4.3 Participant Behavior. At the end of the questionnaire, we asked participants to comment on whether they felt to have behaved similarly or differently in the study's virtual setting as opposed to a comparable real setting. Among those participants who stated to expect a *similar* behavior were both participants who stated that they did not shoulder-surf (as they would also not do this in the real world) as well as participants who admitted shoulder surfing in the real world. Among participants stating that they felt to behave *differently* were four who stated to (at least temporarily) have taken "extreme" positions regarding where they positioned themselves to see the screen. Three participants reported to have been aware of no real person being behind the avatar and, thus, shoulder-surfing. Four participants reported that they would shoulder-surf in both situations, but behave more cautiously in the real world (e.g., not look for extended periods of time). Further comments on aspects that people expected to influence their behavior in the real world were their relationship to the victim and the victim's age.

6 SHOULDER SURFING ATTACK PATTERNS

From our collected data, we found that shoulder surfers follow different attack patterns. In the following, we describe the different patterns and verify them.

6.1 Patterns Description

Pattern 1 – Continuous Attack This attack is characterized by shoulder surfers looking at the screen for an extended period of time with few or no gaze shifts. Such attacks are likely to occur for content which attracts the attention of the user for an extended period of time (e.g., watching a video, reading, playing a game) where, due to the immersion, chances to notice shoulder surfing are rather low.

Pattern 2 – Cautious Attack As users engage in micro interactions (writing short text messages, browsing social media) or as content is more sensitive, chances increase that users either consciously look around them or just look up between different consecutive micro-interactions. We noticed that in such cases, attackers were much more cautious, continuously monitoring the victim's behavior to reduce chances of "being caught" as a shoulder surfer.

Pattern 3 – Repeated Attack A third type of attack is characterized by shoulder surfers looking at the screen for several seconds but to then avert their gaze only to look back after some time. Such attacks occur in cases where victims engage in writing longer messages (emails, real-time chat conversation). Here, attackers check back occasionally to quickly perceive the new content since the last glance, to minimize the chance for being caught. In between, shoulder surfers focus on other things in their visual field of view.

6.2 Pattern Verification

By applying SPAM, we first identified the overall number of attacks per participant and scene per displayed content on the shoulder surfing attack targets. The results are depicted in Figure 2. The most appealing content with its associated total accumulated shoulder surfing time T across all scenes and participants was, in descending order, i) the Football Video ($T = 169.71s, M = 8.49s, SD = 7.11s$), ii) the E-Mail application ($T = 137.26s, M = 7.23s, SD = 4.48s$), iii) the Solitaire Game ($T = 125.97s, M = 6s, SD = 5.66s$), iv) the Tennis Game ($T = 74.26s, M = 5.71s, SD = 5.10s$), v) the Article ($T = 72.06s, M = 5.15s, SD = 4.79s$) and finally vi) the Instant Messenger ($T = 54.71s, M = 5.15s, SD = 4.79s$).

In addition, we report the number of attacks per attack pattern for each scene. Across all participants, we found 444 occurrences of the "repetitive" attack pattern for the office scene and 34 for the bus stop (total: 478). We found the "cautious" pattern 243 times in the office scene and 115 times for the bus stop scene (total: 358). Finally, the "continuous" pattern was found 21 times in the office scene and 11 times in the bus stop scene (total: 32).

6.3 Movement Speed and Gaze Direction

We investigated if people's movement speed and gaze speed differ while shoulder surfing and while not. We first calculated the participants' *movement speed* from the positional change of the x and z coordinates of the HMD in meters per second. Next, we inferred from participants' gaze whether they are performing a shoulder surfing attack (as explained before). We then calculated the mean of participants' movement speed while performing a shoulder surfing attack and while not. A Wilcoxon test showed statistically significant differences ($Z = -2.44, p < .05$). Hence, shoulder surfers move significantly slower at a mean speed of 0.35 m/s compared to non-shoulder surfers at their mean movement speed of 0.38 m/s.

We then analyzed changes in participants' *gaze direction* by calculating the delta over time of the gaze direction, and then calculated the mean value per participant while they perform a shoulder surfing attack and while not. A Wilcoxon revealed a statistically significant difference ($Z = -5.7767, p < .0001$). Participants' gaze direction changes significantly slower while shoulder surfing.

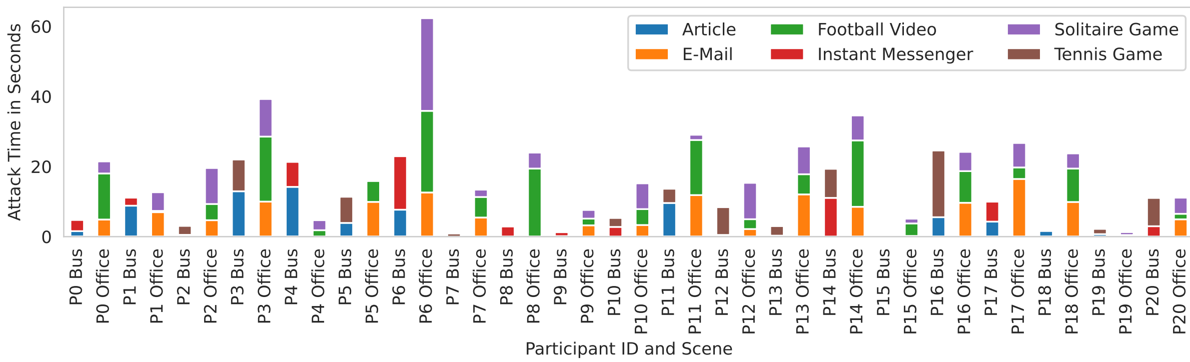

Figure 2: Shoulder surfing attack count for each participant per scene.

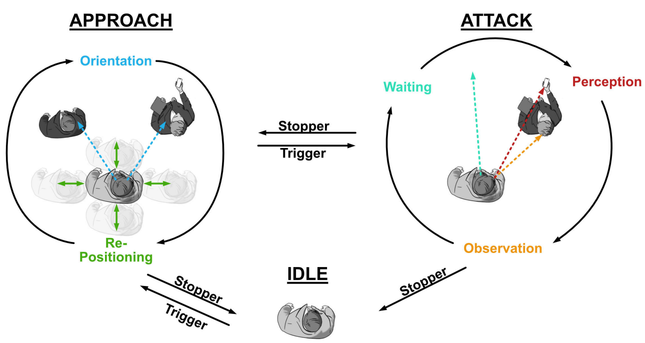

Figure 3: Shoulder surfing attack cycle showing the 3 different attack stages. The idle stage, corresponds to when shoulder surfers are engaged in a non shoulder surfing-related activities, an approach stage is when the shoulder surfing attack is prepared, and then the actual attack stage.

7 TOWARDS A SHOULDER SURFING MODEL

Based on the analyzed data and video recordings of the study, we propose a behavioral model, describing shoulder surfing as a process consisting of different stages. Similar models have been proposed and were constantly being evolved by the community in other areas of HCI [8, 22]. They served as a powerful tool for researchers to guide the design of interactive systems. We expect our model to be a similarly valuable starting point for the community to build upon and to create novel concepts and tools to mitigate shoulder surfing.

Our model consists of three stages: an *idle* stage, where the person is engaged in non-shoulder surfing activities, an *approach* stage in which the shoulder surfing attack is prepared, and the actual *attack* stage. Shoulder surfers are constantly transitioning between the different stages as a result of so-called triggers (ultimately leading to the actual attack) and stoppers. Figure 3 depicts the different stages and their relationship. Below, we describe the stages.

7.1 Idle Stage

The idle stage describes all activities unrelated to shoulder surfing. In our study, examples for an activity belonging to this stage are waiting for the bus or the meeting. In the real world, activities in this stage could include commuting or attending class.

A transition to the next stage – the approach stage – happens as a result of a trigger. Such triggers are, in most cases, visual (e.g., a screen catching a potential shoulder surfer's attention) or auditory (e.g., a notification tone on another person's smartphone).

7.2 Approach Stage

In the approach stage, shoulder surfers alternate between orienting and re-positioning themselves. During *orientation*, shoulder surfers (consciously or subconsciously) decide whether to shoulder surf a victim. *Re-positioning* serves to find a position from which the interaction/content of the victim can be optimally perceived. Positioning can be rather subtle (only moving the head) but could also mean that shoulder surfers walk closer to their victim.

If the shoulder surfers realize that content is not interesting or are not able to get a look at the content, they will transition back to the idle stage (stopper). Else, if they find the content attractive (trigger), they will proceed to the attack stage.

7.3 Attack Stage

The attack stage is characterized by the different attack patterns described above. Generally, shoulder surfers alternate between *observing* the victim and *perceiving* the content (continuous / cautious attacks). This alternation is done to minimize being caught. Optionally (e.g, during repeated attacks), shoulder surfers might enter a *waiting* state in which they wait for further interesting content to become available. After a certain time, they will continue to observe or perceive. The attack stage ends as shoulder surfers, for example, lose interest in the content or are being caught (stopper). In this case, they will transition back to the approach phase.

8 DISCUSSION AND FUTURE WORK

Here, we discuss our findings and directions for future research.

8.1 Shoulder Surfing Acceptability

Some participants considered it acceptable to shoulder surf screens in work contexts, as they expected employees to comply with company regulations. This attitude suggests that the acceptability of shoulder surfing varies across settings. Moreover, there might be little awareness of the implications of shoulder surfing in workplaces. We suggest that shoulder surfing is accounted for in security policies within organizations. Future work could obtain a broader understanding of when shoulder surfing was considered acceptable – both by victims and attackers. This does not only include settings (such as work, home, public space) but also content as well as the relationship between attacker and victim. This information could then be used by approaches to shoulder surfing mitigation to account for acceptability.

8.2 Shoulder Surfing Triggers

We currently have a limited understanding of what triggers shoulder surfing attacks, in particular in cases where these happen opportunistically or casually, i.e., where attackers do not have an explicit intent to shoulder surf. Our findings suggest that shoulder surfing is more likely to occur if the observed screen is close to or in the line of sight of an area that is salient for the attacker. For example, we observed that in the bus stop scenario, the smartphone of the victim that was on the side from which attackers expected the bus to arrive was shoulder surfed more often.

Future work could investigate this in more detail and whether the likeliness to be attacked could be anticipated. For example, a commuter on a train who sits on the window seat might be more likely to be attacked, as the person sitting on the aisle seat might occasionally look out the window to observe the view.

8.3 Attacks Types and Duration

From our analysis, we learn that shoulder surfing takes different forms. These include very short attacks (micro shoulder surfing), which we assume to be a result of attackers orienting themselves and deciding whether the content on the screen is of interest to them. These attacks might still yield private information (e.g., knowledge of the type of content the user is currently looking at). Note that this might happen pre-attentively, i.e., within just a few hundred milliseconds. As shoulder surfers deem content interesting, extended attacks (macro shoulder surfing) occur, where shoulder surfers consciously perceive the content. The duration of these attacks seems to vary depending on the content. Whereas content, such as videos, might lead to persisting attention towards the screen, shoulder surfing instant messages might lead to shorter, repeated attacks.

8.4 The Shoulder Surfer's Sweet Spot

Our analysis shows that people positioned themselves further away from larger screens. This is supported by a phenomenon commonly observed with large display interaction, as people tend to position themselves so that the content can be optimally perceived – a so-called sweet spot [6]. This phenomenon should be further investigated for shoulder surfing, as this sweet spot is likely to be influenced by a variety of factors, such as the fear of being caught and the actual content (e.g., moving closer to be able to read text).

8.5 Ability to Recall

Some participants could recall information from the shoulder surfed content precisely, whereas others could not. This might be influenced by factors like personal interest and other distractions in the environment. This has interesting implications on mitigation concepts. For example, future work could look into whether the fact that shoulder surfers are likely to forget certain information be leveraged or whether forgetting could be supported. Furthermore, future work could try to infer the interest and motivation of shoulder surfers and adjust mitigation strategies accordingly.

8.6 Changes in Gaze and Movement Behavior

We found that during shoulder surfing attacks, movement speed and gaze direction change. This finding could be interesting for the design of approaches to mitigate shoulder surfing. For example, recent works [5, 32, 33] showed that using the front-facing camera, a smartphone could analyze the motion or gaze of bystanders in the visual field of view. A mitigation system could then use a prediction model to identify potential attacks and trigger an intervention.

8.7 Generalizability of Results

Shoulder surfing is difficult to study in the real world. We addressed this by studying shoulder surfing in a controlled VR environment, allowing us to control, manipulate and study the different factors contributing to shoulder surfing. The behavior of participants in our study might be different as opposed to the real world, even though research suggests that VR studies yield ecologically valid results [29]. We strove to minimize any such differences by re-creating situations from the real world and by not making participants aware of our focus on shoulder surfing. We believe our study still yielded exciting insights that otherwise would have been very difficult to identify. These can serve as starting point for future work.

9 CONCLUSION

In this paper, we investigated shoulder surfing using virtual reality. We implemented two waiting scenarios and analyzed participants' gaze and movement behavior in each scene. We assessed the influence of different aspects, namely avatar gender, screen content, and distance. Our investigation allowed us to identify different attack patterns and to propose a behavioral attack model. We found interesting insights regarding shoulder surfer's behavior that could serve as a starting point for further investigations, both on attacker and victim behavior, as well as for designing novel mitigation concepts.

ACKNOWLEDGMENTS

This work was supported by the Royal Society of Edinburgh (RSE award no. 1931), the PETRAS National Centre of Excellence for IoT Systems Cybersecurity, which has been funded by the UK EPSRC under grant number EP/S035362/1, EPSRC New Investigator Award (EP/V008870/1), DFG grant no. 425869382, dtec.bw-Digitalization and Technology Research Center of the Bundeswehr (Voice of Wisdom), and the Studienstiftung des deutschen Volkes.

REFERENCES

[1] Yasmeen Abdrabou, Radiah Rivu, Tarek Ammar, Jonathan Liebers, Alia Saad, Carina Liebers, Uwe Gruenefeld, Pascal Knierim, Mohamed Khamis, Ville Maekelae, Stefan Schneegass, and Florian Alt. 2022. Understanding Shoulder Surfer Behavior Using Virtual Reality. In *Adjunct Proceedings of the IEEE Conference on Virtual Reality and 3D User Interfaces*.

[2] Florian Alt and Emanuel von Zezschwitz. 2019. Emerging Trends in Usable Security and Privacy. *i-com* 18, 3 (2019), 189–195. https://doi.org/doi:10.1515/icom-2019-0019

[3] Adam J. Aviv, John T. Davin, Flynn Wolf, and Ravi Kuber. 2017. Towards Baselines for Shoulder Surfing on Mobile Authentication. In *Proceedings of the 33rd Annual Computer Security Applications Conference* (Orlando, FL, USA) *(ACSAC 2017)*. Association for Computing Machinery, New York, NY, USA, 486–498.

[4] Jay Ayres, Jason Flannick, Johannes Gehrke, and Tomi Yiu. 2002. Sequential PAttern Mining Using a Bitmap Representation. In *Proceedings of the Eighth ACM SIGKDD International Conference on Knowledge Discovery and Data Mining* (Edmonton, Alberta, Canada) *(KDD '02)*. Association for Computing Machinery, New York, NY, USA, 429–435.

[5] Mihai Bâce, Alia Saad, Mohamed Khamis, Stefan Schneegass, and Andreas Bulling. 2022. PrivacyScout: Assessing Vulnerability to Shoulder Surfing on Mobile Devices. In *Proc. on Privacy Enhancing Technologies (PETs)*. Sciendo.

[6] Gilbert Beyer, Florian Alt, Jörg Müller, Albrecht Schmidt, Karsten Isakovic, Stefan Klose, Manuel Schiewe, and Ivo Haulsen. 2011. Audience Behavior around Large Interactive Cylindrical Screens. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI '11)*. Association for Computing Machinery, New York, NY, USA, 1021–1030.

[7] Leon Bošnjak and Boštjan Brumen. 2020. Shoulder surfing experiments: A systematic literature review. *Computers & Security* 99 (2020), 102023.

[8] Harry Brignull and Yvonne Rogers. 2003. Enticing people to interact with large public displays in public spaces. In *Human-computer interaction - INTERACT '03: IFIP TC 13 International Conference on Human-Computer Interaction, 1st - 5th September 2003, Zurich, Switzerland*, Vol. 3. IOS Press, Amsterdam and Berlin.

[9] Frederik Brudy, David Ledo, Saul Greenberg, and Andreas Butz. 2014. Is Anyone Looking? Mitigating Shoulder Surfing on Public Displays through Awareness and Protection. In *Proceedings of The International Symposium on Pervasive Displays* (Copenhagen, Denmark) *(PerDis '14)*. Association for Computing Machinery, New York, NY, USA, 1–6.

[10] Ceenu George, Mohamed Khamis, Emanuel von Zezschwitz, Henri Schmidt, Marinus Burger, Florian Alt, and Heinrich Hussmann. 2017. Seamless and Secure VR: Adapting and Evaluating Established Authentication Systems for Virtual Reality. In *Proceedings 2017 Workshop on Usable Security*. Internet Society, San Diego, CA, USA.

[11] Yi-Lun Chen, Wei-Chi Ku, Yu-Chang Yeh, and Dun-Min Liao. 2013. A simple text-based shoulder surfing resistant graphical password scheme. In *2013 International Symposium on Next-Generation Electronics*. IEEE, Kaohsiung, Taiwan, 161–164.

[12] Malin Eiband, Mohamed Khamis, Emanuel von Zezschwitz, Heinrich Hussmann, and Florian Alt. 2017. Understanding Shoulder Surfing in the Wild: Stories from Users and Observers. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 4254–4265.

[13] Habiba Farzand, Kinshuk Bhardwaj, Karola Marky, and Mohamed Khamis. 2021. The Interplay between Personal Relationships & Shoulder Surfing Mitigation. In *Mensch Und Computer 2021* (Ingolstadt, Germany) *(MuC '21)*. Association for Computing Machinery, New York, NY, USA, 338–343.

[14] Christina Katsini, Yasmeen Abdrabou, George E. Raptis, Mohamed Khamis, and Florian Alt. 2020. *The Role of Eye Gaze in Security and Privacy Applications: Survey and Future HCI Research Directions*. Association for Computing Machinery, New York, NY, USA, 1–21.

[15] Mohamed Khamis, Ludwig Trotter, Ville Mäkelä, Emanuel von Zezschwitz, Jens Le, Andreas Bulling, and Florian Alt. 2018. CueAuth: Comparing Touch, Mid-Air Gestures, and Gaze for Cue-Based Authentication on Situated Displays. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 2, 4, Article 174 (dec 2018).

[16] Mun-Kyu Lee. 2014. Security notions and advanced method for human shoulder-surfing resistant PIN-entry. *IEEE Transactions on Information Forensics and Security* 9, 4 (2014), 695–708.

[17] Nizar R. Mabroukeh and C. I. Ezeife. 2010. A Taxonomy of Sequential Pattern Mining Algorithms. *ACM Comput. Surv.* 43, 1, Article 3 (dec 2010), 41 pages. https://doi.org/10.1145/1824795.1824798

[18] Ville Mäkelä, Rivu Radiah, Saleh Alsherif, Mohamed Khamis, Chong Xiao, Lisa Borchert, Albrecht Schmidt, and Florian Alt. 2020. Virtual Field Studies: Conducting Studies on Public Displays in Virtual Reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI'20)*. Association for Computing Machinery, New York, NY, USA, 1–15.

[19] Diogo Marques, Tiago Guerreiro, Luis Carriço, Ivan Beschastnikh, and Konstantin Beznosov. 2019. Vulnerability & Blame: Making Sense of Unauthorized Access to Smartphones. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–13.

[20] Florian Mathis, Kami Vaniea, and Mohamed Khamis. 2021. Observing Virtual Avatars: The Impact of Avatars' Fidelity on Identifying Interactions. In *Academic Mindtrek 2021* (Tampere/Virtual, Finland) *(Mindtrek 2021)*. Association for Computing Machinery, New York, NY, USA, 154–164.

[21] Florian Mathis, Kami Vaniea, and Mohamed Khamis. 2021. RepliCueAuth: Validating the Use of a Lab-Based Virtual Reality Setup for Evaluating Authentication Systems. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 534, 18 pages. https://doi.org/10.1145/3411764.3445478

[22] Jörg Müller, Florian Alt, Daniel Michelis, and Albrecht Schmidt. 2010. Requirements and Design Space for Interactive Public Displays. In *Proceedings of the 18th ACM International Conference on Multimedia* (Firenze, Italy) *(MM '10)*. Association for Computing Machinery, New York, NY, USA, 1285–1294.

[23] Ildar Muslukhov, Yazan Boshmaf, Cynthia Kuo, Jonathan Lester, and Konstantin Beznosov. 2013. Know Your Enemy: The Risk of Unauthorized Access in Smartphones by Insiders. In *Proceedings of the 15th International Conference on Human-Computer Interaction with Mobile Devices and Services* (Munich, Germany) *(Mobile-HCI '13)*. Association for Computing Machinery, New York, NY, USA, 271–280.

[24] Rivu Radiah, Ville Mäkelä, Sarah Prange, Sarah Delgado Rodriguez, Robin Piening, Yumeng Zhou, Kay Köhle, Ken Pfeuffer, Yomna Abdelrahman, Matthias Hoppe, Albrecht Schmidt, and Florian Alt. 2021. Remote VR Studies: A Framework for Running Virtual Reality Studies Remotely Via Participant-Owned HMDs. *ACM Trans. Comput.-Hum. Interact.* 28, 6, Article 46 (nov 2021), 36 pages.

[25] Philipp A. Rauschnabel, Reto Felix, Chris Hinsch, Hamza Shahab, and Florian Alt. 2022. What is XR? Towards a Framework for Augmented and Virtual Reality. *Computers in Human Behavior* 133 (2022), 107289.

[26] Mudassar Raza, Muhammad Iqbal, Muhammad Sharif, and Waqas Haider. 2012. A survey of password attacks and comparative analysis on methods for secure authentication. *World Applied Sciences Journal* 19, 4 (2012), 439–444.

[27] Volker Roth, Kai Richter, and Rene Freidinger. 2004. A PIN-Entry Method Resilient against Shoulder Surfing. In *Proceedings of the 11th ACM Conference on Computer and Communications Security* (Washington DC, USA) *(CCS '04)*. Association for Computing Machinery, New York, NY, USA, 236–245.

[28] Aitor Rovira, Richard Southern, David Swapp, Claire Campbell, Jian J Zhang, Mark Levine, and Mel Slater. 2021. Bystander Affiliation Influences Intervention Behavior: A Virtual Reality Study. *SAGE Open* 11, 3 (2021), 21582440211040076.

[29] Aitor Rovira, David Swapp, Bernhard Spanlang, and Mel Slater. 2009. The use of virtual reality in the study of people's responses to violent incidents. *Frontiers in behavioral neuroscience* 3 (2009), 59.

[30] A Rovira i Pérez. 2016. *Simulating Social Situations in Immersive Virtual Reality-A Study of Bystander Responses to Violent Emergencies*. Ph.D. Dissertation. UCL (University College London).

[31] Alia Saad, Michael Chukwu, and Stefan Schneegass. 2018. Communicating Shoulder Surfing Attacks to Users. In *Proceedings of the 17th International Conference on Mobile and Ubiquitous Multimedia* (Cairo, Egypt) *(MUM 2018)*. Association for Computing Machinery, New York, NY, USA, 147–152.

[32] Alia Saad, Michael Chukwu, and Stefan Schneegass. 2018. Communicating Shoulder Surfing Attacks to Users. In *Proceedings of the 17th International Conference on Mobile and Ubiquitous Multimedia* (Cairo, Egypt) *(MUM 2018)*. Association for Computing Machinery, New York, NY, USA, 147–152.

[33] Alia Saad, Dina Hisham Elkafrawy, Slim Abdennadher, and Stefan Schneegass. 2020. Are They Actually Looking? Identifying Smartphones Shoulder Surfing Through Gaze Estimation. In *ACM Symposium on Eye Tracking Research and Applications* (Stuttgart, Germany) *(ETRA '20 Adjunct)*. Association for Computing Machinery, New York, NY, USA, Article 42, 3 pages.

[34] Alia Saad, Jonathan Liebers, Uwe Gruenefeld, Florian Alt, and Stefan Schneegass. 2021. Understanding Bystanders' Tendency to Shoulder Surf Smartphones Using 360-Degree Videos in Virtual Reality. In *Proceedings of the 23rd International Conference on Mobile Human-Computer Interaction*. Association for Computing Machinery, New York, NY, USA, Article 35, 8 pages.

[35] Dario D Salvucci and Joseph H Goldberg. 2000. Identifying fixations and saccades in eye-tracking protocols. In *Proceedings of the 2000 symposium on Eye tracking research & applications*. Association for Computing Machinery, New York, NY, USA, 71–78. https://doi.org/10.1145/355017.355028

[36] Ludwig Sidenmark and Hans Gellersen. 2019. Eye, Head and Torso Coordination During Gaze Shifts in Virtual Reality. *ACM Trans. Comput.-Hum. Interact.* 27, 1, Article 4 (Dec. 2019), 40 pages.

[37] Emanuel von Zezschwitz, Alexander De Luca, Bruno Brunkow, and Heinrich Hussmann. 2015. *SwiPIN: Fast and Secure PIN-Entry on Smartphones*. Association for Computing Machinery, New York, NY, USA, 1403–1406.

[38] Keita Watanabe, Fumito Higuchi, Masahiko Inami, and Takeo Igarashi. 2012. CursorCamouflage: Multiple Dummy Cursors as a Defense against Shoulder Surfing. In *SIGGRAPH Asia 2012 Emerging Technologies*. Association for Computing Machinery, New York, NY, USA, 1–2.

[39] Oliver Wiese and Volker Roth. 2015. Pitfalls of Shoulder Surfing Studies. In *Proceedings 2015 Workshop on Usable Security*, Jens Grossklags (Ed.). Internet Society, Reston, VA.

[40] Bob G. Witmer and Michael J. Singer. 1998. Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence: Teleoper. Virtual Environ.* 7, 3 (jun 1998), 225–240. https://doi.org/10.1162/105474698565686

[41] Dhruv Kumar Yadav, Beatrice Ionascu, Sai Vamsi Krishna Ongole, Aditi Roy, and Nasir Memon. 2015. Design and Analysis of Shoulder Surfing Resistant PIN Based Authentication Mechanisms on Google Glass. In *Financial Cryptography and Data Security*, Michael Brenner, Nicolas Christin, Benjamin Johnson, and Kurt Rohloff (Eds.). Springer Berlin Heidelberg, Berlin, Heidelberg, 281–297.