Human Factors in Security Research: Lessons Learned from 2008-2018

Mannat Kaur, Michel van Eeten, Marijn Janssen, Kevin Borgolte, and Tobias Fiebig
{M.Kaur, M.J.G.vanEeten, M.F.W.H.A.Janssen, K.Borgolte, T.Fiebig}@tudelft.nl
TU Delft

Abstract—Instead of only considering technology, computer security research now strives to also take into account the human factor by studying regular users and, to a lesser extent, experts like operators and developers of systems. We focus our analysis on the research on the crucial population of experts, whose human errors can impact many systems at once, and compare it to research on regular users. To understand how far we advanced in the area of human factors, how the field can further mature, and to provide a point of reference for researchers new to this field, we analyzed the past decade of human factors research in security and privacy, identifying 557 relevant publications. Of these, we found 48 publications focused on expert users and analyzed all in depth. For additional insights, we compare them to a stratified sample of 48 end-user studies.

In this paper we investigate: (i) The perspective on human factors, and how we can learn from safety science; (ii) How and who are the participants recruited, and how this—as we find—creates a western-centric perspective; (iii) Research objectives, and how to align these with the chosen research methods; (iv) How theories can be used to increase rigor in the communities scientific work, including limitations to the use of Grounded Theory, which is often incompletely applied; and (v) How researchers handle ethical implications, and what we can do to account for them more consistently. Although our literature review has limitations, new insights were revealed and avenues for further research identified.

I. INTRODUCTION

Traditionally, computer security concerned itself with understanding the technical properties of systems and networks in order to guarantee confidentiality, integrity, and availability. With the rapid societal adoption of computer systems over the past decades, researchers identified new security and privacy issues, stemming from the interaction between users and systems. This gave rise to the study of human factors. In this context, most research emerged as part of either (i) designing secure and usable systems, or (ii) empirical studies of problems around how users interact with systems and services.

The first approach is design-oriented. Data on users is collected as part of a design process or an evaluation of an existing system. Think of eliciting user requirements or validating the performance of the designed system with actual users. Organized around the concepts of usability and human-computer-interaction, researchers have worked on creating secure and usable systems. A classic example is Whitten and Tygar’s usability analysis of GPG’s user interface [150].

The second approach to human factor research is descriptive, i.e., focuses on soliciting empirical data on users’ behavior. Users are studied in various security-relevant contexts, to learn more about their behavior in general, not directly tied to the design process of a specific system or service. This work typically relies on experiments, surveys, and observational data. For example, Krombholz et al. conducted experiments to see if system operators are able to properly deploy HTTPS [82] Dietrich et al. surveyed system operators’ perspectives on security misconfigurations [33], and Golla et al. collected behavioral data around password reuse notifications from a production system [52].

Large-scale security incidents are often traced back to human error, like mistakes or forgetfulness [13, 68, 102, 109, 141]. The status quo approach to managing the human factors in cybersecurity says that humans are the weakest-link in security. Numerous efforts are made to eliminate, control or train the human factor in order to improve security [156]. Such human-factors studies have been a steady presence in the main security and privacy venues in the recent past. In fact, the portion of published work that includes user research has more than doubled over the past years. But what all constitutes human factor research? How has the field evolved in the recent past and what are the research gaps that still exist?

We focus our analysis of the state of the art on one critical population in human factors research: experts. By experts we mean the people who develop, build and run systems (a more precise taxonomy is developed in Section II). Their errors can be highly consequential, as they can impact many systems at once or impact critical systems, on which many users and organizations rely. To better locate the studies on experts in the overall field of human-factors research, we also analyze a sample of end-user studies and compare both types of research throughout our paper.

Investigating human factors is not one of our community’s traditional areas of expertise and other disciplines have been studying human factors since much longer. Research in these domains have shown that the "weakest-link" approach is not the only way to manage the human factor [25]. This provides an opportunity for our community to learn from more mature areas which have investigated human behavior for many decades. Valuable lessons can be gained from safety science, which is an engineering-dominated discipline that aims at preventing adverse outcomes, similar to security, but with a substantially longer track record of incorporating human factors (discussed further in Section III and Figure 2).

Research that crosses over from computer security to these other fields is still rare. Examples include Egelman
and Peer, who developed a Security Behaviour Intentions Scale (SeBIS) that measures users’ attitudes towards various computer security tasks [37], and Hárnornik and Krasznay, who developed a research framework linking computer-supported collaborative-work (CSCW) and team cognition in high risk situations to better understand teamwork in security operation centers (SOCs) [60]. However, our community can build more systematically upon the work in social and safety sciences to leverage their theories and methods and to increase scientific rigor and generalizability, which are issues plaguing “security as a science” as pointed out by Herley et al. [66].

Our research question for this paper is: What is the state of the art of human factors research on experts in the computer security domain and what lessons can we learn for future research? We analyze the current state of human factor research in computer security to serve as a point of reference for new and established researchers alike. We review the literature on six aspects and answer the following sub questions:

1) What insights from the safety science domain can be applied to the computer security domain?
2) What sample populations are being investigated and in what ways are they recruited?
3) What is the objective of the research?
4) What are the research methods that the researchers are using to study users?
5) What kind of theories, if any, are the researchers using and how?
6) How did the researchers evaluate the ethics of their work? Whether it be design-oriented or descriptive work, we first want to account for all the human factors research and create an overview of the state of the art. We scope our work by identifying papers that directly involve people in the main computer security venues from the past ten years. We end up with 557 publications in total. Then we group these papers based on the population they investigate, i.e., whether the paper deals with end users or expert users. End users are the focus of 91.4% of the papers, while expert-user studies make up a mere 8.6% of the publications. We systematize the state of the art for the expert user group and analyze all of the 48 papers in depth. For comparison, we also review a sample of end user papers. Since we cannot analyze all the 509 papers in depth, we have chosen a stratified random sample of 48 end-user publications. Subsequently, for each category, we provide recommendations on how the field can further mature. Our key contributions are:

1) We find that expert users, different from end users, are an understudied population in terms of human factors in computer security, even though their behaviors and mistakes have higher stakes and more severe consequences.

2) We also find that papers on expert users commonly treat human error as a root cause to be removed from the system. This is an opportunity to learn from safety science research where the focus is to better understand the human factor and in turn build resilient systems that produce the desired outcome despite human error.

3) Similar to other fields, we find that the recruitment of study participants is dominated by convenience sampling and has a geographical bias towards the US and Europe, which threatens international generalizability.

4) Most human factors research (78.12%) lacks theory to inform research design and causal reasoning. Even research that utilizes Grounded Theory regularly stops before the step of building a theory from the empirical findings. The absence of theory limits the generalizability of the findings beyond the context of the study itself.

In addition, we release the annotated version of our list with 557 human-factors studies in security and privacy as open data along with this paper.

II. Paper Search and Selection Process

In this section, we present our approach to building a representative corpus of human-factor studies and present the analysis criteria for our subsequent analysis.

A. Search Process

We perform a systematic literature review (SLR), inspired by Kitchenham et al. [80], to identify publications on human factors in computer security. Figure 1 presents an overview of the major steps of our selection and filtering process.

Inclusion and exclusion criteria

First, we perform an comprehensive search across the most prominent computer security venues. Specifically, we selected all top-tier (Tier 1 and 2) computer security and network operations venues, based on a common ranking.1 We consider venues that purely focus on cryptography, like Crypto or TCC, as out of scope. Furthermore, we did not include workshops, as for example USEC, as our goal is comprehensiveness, not completeness, even though they also publish a sizeable number of human factors related security work. We do, however, add the Symposium on Usable Privacy and Security (SOUPS, Tier 3) to this list, as it is a major venue for usable security. We also add ACM CHI, the Conference on Human Factors in Computing Systems, which is the “premier international conference of Human-Computer Interaction.” Overall, we reviewed the proceedings of 14 conferences from 2008 to 2018, resulting in an initial set of 11,188 papers. We specifically chose to limit our search scope to this period because we want to investigate the current development of the field. Also, we do not present search keywords because all the papers were selected from these venues. Next, we reduce the set of papers to 6,606 papers, by only including papers from ACM CHI that are presented in sessions related to security, privacy, passwords, and authentication. We acknowledge that this might lead to individual papers within CHI being omitted. However, to set a reasonable scope for the literature review, this limitation was necessary. We read the title and abstracts of all 6,606 papers to identify those that investigate human factors. The key criterion is the direct involvement of humans

1See http://faculty.cs.tamu.edu/guofei/sec_conf_stat.htm. The list was updated after we had finished our search and now has 18 venues in tier 1 and 2, instead of 17. We acknowledge that this list does not constitute an ‘official’ ranking, yet is commonly used within the community, even though it is critically acclaimed by some for its selection of venues.
in the research, both online and offline, to study behavior or actions. This means we exclude papers that only perform large-scale internet measurements to understand user behavior. Furthermore, we also exclude papers that do not contain full-fledged user studies, for example Czyz et al., who perform an unstructured inquiry via email to identify root causes of IPv4/IPv6 security misconfigurations [22]. Ultimately, this selection process took over 1,300 working hours. We identified 557 papers on human factors in security (see Table I for an overview). We will publish our annotated literature database along with this paper. Finally, we discuss the limitations of our search process in Section IX.

B. End Users and Expert Users: A Taxonomy

Here, we developed a taxonomy of what users are being studied to explain how we arrive at the distinction between “expert users” and “end users” which we use for segmenting and sampling the literature in the next section. This categorization is based on the task that is being studied, rather than on inherent properties of the user who participates in the study. If the task is part of expert work, then we include the study as an expert study. This means that even when a person which could be classified as a “security professional”, if this person is participating in a study of an email user interface, this participation would not make the study an “expert-user” study. Similarly, studies that subject “non-experts” to expert tasks, like vulnerability discovery in the case of Votipka et al. [143], do not become “end user” studies because of the utilized population.

- **Expert Users (Building Systems):** Expert users are those that build and run systems. Contrary to end users, they directly influence the security of systems used by someone else. Studies in this category deal with tools exclusively used in this context, that is, the process of providing a system for a third party (end users), and the processes and behaviors associated with the process of running these systems.

  - **Developers:** Developers write the code for end user visible applications as well as the back-end systems that make these tools function. A common sub-distinction for developers is frontend vs. backend developers.
    - **Frontend Developers:** Developers who work on the user interface of applications.
    - **Backend Developers:** Developers who work on the backend, that is, they create application programming interfaces (APIs) that can be used by the frontend to handle database interactions and business logic.

- **Fullstack Developers:** Developers versed in frontend and backend tasks.

- **Operators:** Operators are those running systems. They deploy and update software created by developers, configure network equipment, and provide services to users. We note, that this distinction is difficult. On the one hand, we see that the community often utilizes “developers” as a covering term for everything that involves building and running a service or application, thereby covering operators. On the other hand, recent developments in how we run systems more and more merge the concept of operations and development, that is, DevOps [136]. Below, we provide a non-exhaustive set of examples of operators.

  - **System Operators:** System operators operate systems in general, akin to fullstack developers, that is, they take care of systems from several of the following categories.
  
  - **Network Operators:** Network operators deal with network infrastructure, that is, they configure network switches and routers, and are usually also in charge of designing the physical network.
  
  - **Client Operators:** Client operators are among the most visible operators of an organization, as they deal with provisioning and providing patches to workstations, which are the most user-visible activities.
  
- **Help Desk Personnel:** Help desk personnel is commonly the first point of contact for users. Although help desk staff does not fall into the “traditional” operator categories, they often receive some operational permissions to handle common user requests.

- **Security Experts:** While security professionals constitute their own class, they often overlap with other roles from development or operations. However, due to the context of our work, we detail them as a dedicated class.

  - **CSIRT/SOC Workers:** Computer Security Incident Response Teams (CSIRTs) and Security Operations Center (SOC) workers handle threat intelligence feeds and incident reports received by an organization and follow up on potential threats.

  - **Red/Blue Team Members:** Red and blue team members conduct assessments of an organization. While red teams attempt to gain access to systems
as “attackers,” blue teams audit infrastructures to identify security issues and “defend.”

* Residential Security Experts: Residential security experts often overlap with blue team work, and they are members of an organization who are in charge of assessing and reviewing security sensitive changes in code bases or concerning infrastructure.

– Researchers: Some papers study computer-security researchers as their sample population. These studies account for the researchers’ perspective in the computer security domain.

– Computer Science (CS) students: Many of the studies recruit computer science students as a proxy for expert users. These students have a technical background and are a convenient sample in academic research.

– Others: The remaining studies are categorized as ‘other’. These include experts from various organizations such as those that develop cryptographic products [62], studies that perform participant observation inside the organization [131], studies that include hackers [92] etc.

• End Users (Using Systems): This group contains *users* of systems. This means that this group is not involved with *running or changing* the systems they use, and they use these systems for personal—in a private and professional context—activities, such as reading or encrypting one’s emails.

– Applicable Subgroups: For end users, various population slices are applicable. This ranges from studies of the elderly and their security behavior [47] to children [83], and it includes classifications of profession related subgroups, like journalists or aid workers. We identified the following sub-groups for our study, namely: the general public, university students/staff, specific users groups like journalists or air workers and children.

Improving human factors clearly requires different approaches and solutions for expert tasks compared to regular end-user tasks. One can design very different solutions given the stark contrast in training and competencies of experts compared to end users. Furthermore, the stakes of individual human errors of experts are often higher. A simple error during the operation of a system of the development of software can easily affect hundreds to thousands to even millions of users. This, in turn, may have a significant impact on how human factors need to be treated for these two different populations.

C. Dataset Overview and Sampling

The first observation we can make is that human factors research is on the rise, both in an absolute and a relative sense. Starting at 21 papers in 2008 (3.4% of all studies in the selected venues), the number of human factors papers rose to a total of 88 in 2018 (6.1%). Naturally, most of these papers appeared in SOUPS (198) and ACM CHI (133). We do not consider all SOUPS papers because not all include user studies, that is, users were not directly involved in the research, for example, in the case of literature surveys and position papers.

From a human factors perspective, different user populations present different challenges, which also implies the need for different theories and methods. The most important distinction we encountered across the corpus of papers is between expert users and end users, see Section II-B. End user studies typically concern themselves with topics like interfaces used by the general population, or user behavior around widely-used technology. In contrast to end users, expert users do have prior knowledge, training, or experience in software or hardware engineering, networks, or systems operations, which they use to build systems.

Overall, we find that end user studies considerably outweigh expert user studies: 509 of 557 papers deal with end user (91.4%), while only 48 papers (8.6%) concern themselves with expert users. The lack of human factor research on expert users is alarming. While numerically clearly a smaller group, the behavior of expert users typically affects more systems than just their own, thus having a comparatively larger impact on security than individual end users. For example, system administrators making security misconfigurations can affect thousands or more regular users. For our study, we review all the 48 expert user studied in depth. To gain additional insights, we have also reviewed a group of end user papers. Since we cannot analyze all the 509 papers in depth, and the two groups are imbalanced, we have chosen a stratified random sample of 48 end-user publications. Stratification was done by publication year, that is, we matched the distribution of expert user papers over time by randomly choosing papers from the end user group corresponding to the number of expert user papers per year. To illustrate: since two papers on expert users appeared in 2008, we randomly selected 2 out of 19 end user publications in 2008. We acknowledge that this might limit our view on the literature on end users. However, given the vast body of existing literature, an exhaustive analysis is infeasible, and a stratified sample based on the temporal distribution of the expert user sample provides a reasonable trade-off between reliability and feasibility.

D. Analysis Criteria

We analyze the literature on six aspects: The general perspective on human factors, the sample used in the study, how this sample has been recruited, the research objective, how the authors utilized existing theory or methodology to inform their research design, and, ethical considerations.

Perspective on Human Factors: In safety science, decades of research has fundamentally changed the understanding of human factors and human error. The current perspective of safety science sees human error not as avoidable, but as a property of human work, which systems have to account for to ensure safe operations in the presence of error. This evolution is summarized in five major stages, which we discuss in the next Section (see also Figure 2). We analyze how research on human factors in computer security compares to this understanding from safety science.
Table I: Literature on human factors in security (HFS) vs. all papers, for major security venues between 2008 and 2018. For each year we list the number and share of HFS papers for that year, and how they are distributed over end users and expert users.

| Conference | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | Total |
|------------|------|------|------|------|------|------|------|------|------|------|------|-------|
| ACM AsiaCCS| 40   | 1    | 40   | 3    | 2    | 61   | 5    | 50   | -    | 71   | 8    | 62   |
| ACM CCS    | 52   | 1    | 58   | 1    | 61   | 3    | 81   | 6    | 96   | 5    | 138  | 4    |
| ACSAC      | 45   | 1    | 48   | 1    | 42   | 3    | 41   | 3    | 43   | 1    | 40   | 4    |
| EEE DSN    | 1    | 58   | -    | 64   | -    | 51   | -    | 68   | -    | 50   | -    | 60   |
| ESORICS    | 1    | 37   | -    | 42   | -    | 36   | -    | 43   | -    | 38   | -    | 60   |
| IEEE CSF   | -2   | 22   | -    | 22   | -    | 21   | -    | 19   | 2    | 29   | -    | 22   |
| IEEE S&P  | 28   | 1    | 26   | 1    | 34   | 2    | 34   | 1    | 44   | 1    | 55   | 3    |
| ACM IMC    | 31   | 1    | 41   | -    | 42   | 4    | 45   | -    | 42   | 4    | 42   | 42   |
| ISOC NDSS  | 21   | 1    | 20   | -    | 24   | 1    | 46   | 5    | 50   | 2    | 55   | 3    |
| PETS       | 13   | 1    | 14   | -    | 24   | 1    | 15   | 1    | 13   | 4    | 16   | 23   |
| RAID       | 20   | 3    | 17   | -    | 16   | 1    | 20   | 1    | 22   | 1    | 15   | 21   |
| SOUPS      | 10   | 12   | 14   | 15   | 14   | 15   | 14   | 15   | 21   | 21   | 22   | 22   |
| USENIX Sec. | 27  | 21   | 26   | 2    | 30   | 1    | 35   | 4    | 43   | 1    | 44   | 2    |
| ACM CHI     | 8    | 218  | 7    | 277  | 10   | 302  | 15   | 409  | 7    | 369  | 5    | 392  |

HFS papers (%): 21 (3.4%), 29 (4.1%), 30 (4.0%), 38 (4.4%), 38 (4.0%), 56 (3.0%), 59 (5.1%), 75 (5.8%), 78 (5.7%), 88 (6.1%), 557 (5.0%).

End Users: 19 (3.4%), 26 (4.1%), 29 (4.0%), 42 (5.1%), 39 (4.4%), 38 (4.0%), 56 (3.0%), 59 (5.1%), 75 (5.8%), 78 (5.7%), 88 (6.1%).

Experts: 2 (3.4%), 3 (4.1%), 1 (4.0%), 2 (5.1%), 1 (4.4%), 3 (4.0%), 56 (3.0%), 59 (5.1%), 75 (5.8%), 78 (5.7%), 88 (6.1%).

Study Population: Naturally, we also investigate the samples used in contemporary research. We identify the major types of populations based on how authors describe their samples. This taxonomy is discussed in Subsection II-B. For end users, these groups are “children” (minors), the general public, university-affiliated users (like staff and students), and other specific user groups. For example, some studies focus on users with social disorders [99], South Asian women [120], or users in relationships [84, 105]. If no information about the sample population is available, then we mark the population as “N/A.”

For expert users, we broadly differentiate between developers, operators, security professionals, researchers and computer science students. Each of these categories is explained, along with the subcategories, in Subsection II-B. When studies compare expert users to end users, a confusing edge case, we classify them as “end users” among the expert-user publications. The remaining studies on expert users we categorize as “other”. This includes studies where a set of different experts from a specific organization or set of organizations are involved [62, 130, 131], technical experts and end-users are recruited for a comparison study and their expertise is not specified [127], or a study with hackers and testers [143]. As an additional point of reference, we also identify the geographic region from where samples are collected, and where the authors themselves are located.

For our analysis, we only consider the broad categories and not the subdivisions. For example, we talk about frontend, backend and fullstack developers in our taxonomy. During the analysis however, we broadly classify all these under the developer category.

Recruitment: We analyze how researchers recruited participants. For end users, we consider recruitment via crowdsourcing platforms (like Amazon Mechanical Turk, or other crowdsourcing platforms like CrowdFlower [7, 16]), recruitment in the local city, at the local university, via personal contacts, a recruitment agency, social media, or “other” online channels. For example, these online channels can be Craigslist [50, 139, 157], Sampling Survey International [114], or simply using other non-crowdsourcing platforms online, like message boards.

Similarly, for expert users, we distinguish between crowdsourcing platforms, GitHub, the local university, personal contacts, industry contacts or industry organizations, social media, and “other” methods. Other recruitment methods include recruitment at a conference [62, 82], public bug bounty data [143], or establishing an online brand [33]. In case the authors fail to provide sufficient recruitment information, we mark it as “N/A.”

Research Objective: Concerning the research objective, we distinguish between studies that (i) evaluate an artifact, (ii) test hypotheses, (iii) perform general exploratory research, and (iv) focus on gathering users’ perspective on specific issues. Moreover, if authors evaluate an artifact, we check if they used an existing research framework for building and evaluating the artifacts, such as design science, and whether they include user feedback or evaluation results in the design of their artifact.

Research Method: We systematize how researchers conduct their studies by distinguishing between studies performed in a local laboratory, online, using interviews, surveys (including questionnaires), focus groups, or using observations. One study can have multiple research methods.

Theory/Framework: Regarding the use of theories and frameworks, we scrutinize how authors use existing scientific theories. Specifically, we investigate if they (i) use an existing theory to inform their research design or set out to validate and improve upon an existing theory, (ii) mention an existing theory in the context of their results and observations, or (iii) neither use or mention a theory. In our analysis, we identified three major theories (Mental Models, Sensemaking, and the Theory of Reasoned Action). Furthermore, we closely study work that claims to use grounded theory, which is a methodology that creates theory through a systematic process of data gathering and interpretation. Correspondingly, we do not mix it with the use of existing theories, but add an additional category, in which we explore whether authors (i) focus on the methodological parts of grounded theory to obtain observational results and generally inform their qualitative data analysis, (ii) use a
“middle ground” approach [122], in which they contrast their findings with existing theories, or (iii) perform grounded theory to construct a new theory or model.

**Ethics:** Finally, we study whether the authors considered the ethical implications of their work. We distinguish between (i) authors that obtained full clearance from their ethical review board, (ii) those who discuss the ethical implications but did not or could not obtain a clearance from a review board, e.g., because their institution does not have one., and (iii) authors who do not discuss the ethical implications of their work.

### III. Perspective on Human Factors

Research on human factors has emerged in safety science decades earlier than in computer security, which bears the question: What can we learn from safety science? In this section, we first present the safety science perspective accompanied with a visual aid (Figure 2). We then present the computer security perspective on human factors research and what we observed in our literature review. This is followed by a discussion on the synthesis of these two perspectives. We discuss what we can learn from other domains and also insights that cannot be directly applied. Finally, we present our key observations and recommendations at the end of the section.

#### A. Safety Science Perspective

Initially, the term *human factors* described the application of scientific knowledge, concepts, models, and theories derived from social science disciplines, such as psychology, towards improving operational efficiency and reducing the human errors that led to accidents [5]. This early literature on human factors and human error has since gone through five major stages of development in the past century (Figure 2).

For the first half of the 20th century, the core ideas were that certain people are prone to accidents and accidents are preventable by taking away the causes, for example, enforcing compliance with rules. These ideas developed further and gave rise to the concepts of decomposable systems (a linear model where cause and effect is visible and wherein the system can be decomposed meaningfully into its parts and rearranged again into a whole) and bi-modal functionality (the components of the system can be in one of two modes of operation - either functioning correctly or not). These two concepts led to the assumption that every failure has a root-cause and if we can find this root-cause, we can fix it and ensure safety. In this case, the analysis is centered around the individual responsible for “human error” or failure.

During the second half of the century, the systems perspective emerged, and did the label of “human-factors research.” This changed the narrative from who is responsible to what is responsible, shifting the focus on the latent conditions behind failure. The analysis now included both individual and organizational aspects.

Since the 2000s, the safety science domain has witnessed another shift in paradigm. The new perspective on safety is known as Safety-II. The Safety-II approach takes into account what is responsible for success. Instead of creating the best way for people to comply, researchers take a step back to understand people and their variable performance in safety or security-critical operational environments. The Safety-II approach does not replace the traditional approach to safety that has developed over the decades. It is a complementary approach with a focus on proactive safety management. In addition, we also see a shift in the way in which we deal with human error. Restorative Justice is an approach that focuses on repairing the harm through accountability and learning instead of responsibility and blame. Also included now are the societal parameters in the analysis of human factors.

A key take-away from the contemporary perspective is that trying to eliminate the human factor to build safe and secure systems is not the only way to improve safety. It is also important to understand why systems do not fail, in daily operations as well as in the presence of human error, and understand how the human factor contributes to success.

#### B. Computer Security Perspective

We know that people are considered the weakest-link in computer security and many large-scale incidents/breaches are often blamed on human error. This holds true for both end users and expert users. Currently the most common solutions to this human problem are to eliminate the human-in-the-loop, training and education, compliance via policies and root-cause analysis (reactive security) [156]. When mistakes occur, the route to security is to eliminate these mistakes by adding automation, protocols, or standards, thereby often even introducing new challenges for the secure operation of systems [33]. For example, when an automated system behaves differently than expected by its operator. This negative impact of automation is known as “automation surprise”.

To be able to classify human factors in computer security literature more easily, we condense the perspective of safety science in the following way: a) eliminating the human factor, that is, preventing errors, b) investigating the human factor to understand what makes things go the way they go and c) neither of these perspectives is identified. We marked papers trying to “eliminate” the human factors in column “HF Persp.” with a ● and those that are trying to understand the real-world phenomenon with a ○ under “Theory/Framework” in Table II and Table III. If neither of these perspectives is identified, the paper is unmarked.

We find that eleven papers in the expert-user sample take the elimination perspective, as opposed to one paper from the end-user studies, see Figure 3. These papers set the premise of error elimination by proposing complete or partial automation [41, 42, 53, 82, 100, 151], emphasizing the role of policies, systems and frameworks [51, 77] or focusing on “human error” as the root cause [40, 95]. We connect this observation to how we, in general, perceive experts and end users. Professionals are expected to be knowledgeable and trained enough to not make mistakes. Researchers, especially from the engineering field, implicitly assume experts should know better than to make certain mistakes in the operation and creation of systems.
Accident proneness[21, 25, 75, 96, 104, 127, 135, 143, 149], organizational factors [38, 76, 99], culture. These approaches are important because accounting for the sociotechnical factors creates a more realistic description and better equips us to deal with the operational uncertainties.

The end-user studies look at user perspectives around the security and privacy challenges of emerging AR technologies [84], layman’s understanding of privacy [101], user behavior and opinions on the adoption of two-factor authentication [18] and whether social disorders influence social engineering [99], to name some examples. Just as expert-user studies, these papers provide important insights into users’ perspective and real-world concerns.

C. What can computer security learn from safety science?

Despite all our efforts, serious security breaches and hacks continue to happen. Some contemporary research has emphasized the need to rethink the status quo and challenge the core assumptions underlying our current approach. As discussed earlier, the traditional safety science approach sees people as the problem and assumed that systems are decomposable and bimodal. Zimmerman and Renaud argue that cybersecurity, currently has similar assumptions underneath [156].

Human factors research in the computer security domain is interdisciplinary. We are studying sociotechnical systems that are complex, unpredictable and emergent. Due to this, the traditional assumptions (human as problem or decomposability) do not work well.

Zimmerman and Renaud propose the cybersecurity, differently approach. Drawing learning from other fields such as military, management and safety, they present some key principles of this new approach. These are system emergence (vs. system decomposability), human as solution (vs. human as problem), deference to expertise (vs. policy compliance), encourage learning and communication (vs. constrain and control), focus on success (instead of solely preventing errors) and finally, balancing resistance and resilience [156].

As explained before, the Safety-II approach does not replace the traditional approaches to safety but is complementary. Similarly, the cybersecurity, differently approach is not about radically changing the way in which we manage computer security. It is about recognizing the sociotechnical aspects of computer security when addressing the human factors. We
must broaden our perspective on the management of human factors and explore modern principles along with traditional ones.

Finally, are there some learnings that cannot transcend from another domain to the computer security domain? The human problem in the safety domain focuses on unintentional mistakes by well-intended humans. The case of intentional harm and sabotage is not addressed in this approach and is seen as a separate security concern. However, the computer security domain deals with both malicious actors and non-malicious human error. Therefore, we need to remember this knowledge transfer does not address dealing with malicious actors.

D. Observations and Recommendations

Key Observations: We find that past research on expert users mainly took an eliminatory stance. That is, the research tried to remove the human factor from systems, for example, by introducing automation. This approach is losing steam in safety science research, mostly based on the insight that the human factor cannot be ultimately eliminated, and, therefore, systems rooting their safety and security in this are ultimately never really safe. Fortunately, the situation is better for end-user related work, which hardly takes the traditional perspective of eliminating the human factor and focuses on usability studies and learning the users’ perspective.

Key Recommendations: Given how often human error is considered to be the root cause of security vulnerabilities, we encourage the field to rethink the perspective that we take concerning human factors in computer security, especially when studying expert users. One key takeaway is that in addition to preventing human error, we should also try to understand which behavior leads to secure outcomes, and how we can facilitate that behavior. To accomplish this, we will have to investigate—especially expert users—in their daily interactions with the tools and issues we focus on, something that is hardly done at the moment (see Section VI).

IV. Sample Population and Recruitment

Next, we look at the population samples, that is, who researchers investigate and how they recruit the participants.

Our results are summarized in columns “Sample” and “Recruitment” in Table II and Table III, and we visualize the geographic distribution of authors in Figure 4.

A. Population Selection and Recruitment

In the expert-user studies sample, we discover that Computer Science students and security experts are the most utilized populations. This holds true even for end-user studies. In other words, university students are the most popular population sample being studied for both expert and end-user studies. This is to be expected: members of the (local) university are easily accessible for university researchers, that is, they constitute a convenience sample. Interestingly, only one of the papers is specifically studying college students as their intended research subject [110], while the remainder used them as a convenient proxy for end-user and expert-user populations.

Regarding recruiting participants from these populations, we identified eight categories for both expert and end-user samples, though not exactly the same categories. For expert-user research, the most popular recruitment method is via personal contacts and university channels. We note that it seems to be convenient to find experts through one’s personal networks, specially for researchers working in the same field of expertise. For end users, university channels, like local (physical) message boards and on-campus recruitment, are the most popular recruitment method, followed by Amazon MTurk. Similar to the reason why university students are most studied, this is probably due to the fact that university channels are a convenient recruitment method.

B. Population Location

We find that in a large number of the studies, the population sample is based in North America or Europe. Only four end-user and expert-user studies each report an international population sample. Hence, overall, the western user population is the most represented. This follows from our observation on convenience sampling, as we also see that most research itself is contributed by authors from the U.S. and, to a lesser degree, Europe. In Table II and Table III, we mark western authors and populations with ☺, authors and populations from other regions with ☼, and international collaborations and populations with ☻.

In our analysis of the end-user studies, we find that the majority of the eleven papers where the location of the population is not reported, are studying “specific users” (see Figure 4). Specific users, as explained earlier, refer to users of specific online channels, such as MTurk or the Security Behaviour Observatory, or other specific groups, like users with social disorders. For expert users, the group of papers not specifying the location of the studied population is even larger (24/48) (see Figure 4a).

A likely explanation for this imbalance is that “expert users” are a form of “specific users.” We conjecture that it is difficult to report the location of the population when people are recruited through online channels, which is the case in a large number of the expert-user studies. Similarly, when selecting for a specific type of users, expert or end-user alike, it may seem reasonable to not focus on the users’ location. However, even when investigating specific users using an online service, the authors’ location may predetermine the recruited population’s location, for example, due to the language used for recruitment, or due to the service used being biased towards a population, like Amazon MTurk [113].

C. Challenges in Recruitment

In end-user studies, recruiting a representative sample is difficult, as the use of technology is inherently global and cultural differences may influence the effectiveness of security measures [52]. In this case, it is better to acknowledge the limitations of one’s population sample and report on the resulting restrictions on the generalizability of the results.
For expert-user studies, representativeness is even more challenging. Recruitment channels are more limited and willingness to participate is often reduced due to the high workload of experts [33].

In their work on exploring a convenience sample, Acar et al. [4] further discuss the challenges in recruiting participants for expert-user studies. Different from end-user studies, where recruitment is fairly straightforward (MTurk, posting flyers, classifieds etc.), no well established recruiting processes exist for expert-user studies [4]. This is because it can be difficult to contact and invite professionals for in-lab studies, to find professionals locally, find free time in the experts’ schedule or simply to provide enough incentives [33]. These observations close the loop to our earlier remarks on convenience samples, such as from a local university or via personal contacts: It is simply easier. However, when following this path, it is imperative to account for the limitations this introduces for the external validity of the obtained results.

Table II: Overview of expert related human factors in security research.

| Year | Ids. | Ref. | Sample | Recruitment | Res. Obj. | Research Method | Theory / Framework |
|------|------|------|--------|-------------|-----------|-----------------|-------------------|
| 2008 | E1 [148] | | Developers | | | | |
| 2009 | E3 [38] | | Operators | | | | |
| 2010 | E6 [76] | | Researchers | | | | |
| 2011 | E7 [70] | | | | | | |
| 2012 | E9 [151] | | | | | | |
| 2013 | E10 [41] | | | | | | |
| 2014 | E12 [75] | | | | | | |
| 2015 | E15 [130] | | | | | | |
| 2016 | E20 [24] | | | | | | |
| 2017 | E24 [48] | | | | | | |
| 2018 | E32 [61] | | | | | | |

Legend: Location: Western (Europe, North America); Non-Western; International (Multiple Regions); No Marker: Unknown; External Validity: Considered and addressed; Mentioned as a limitation; Not discussed; Methods: Mixed Methods; Quantitative; Qualitative; Theories: Used; Mentioned; Suggested; Grounded Theory: Full; Middleground; Analytical; Evaluation of Artifact: Before and After; Before; After; HF Perspective: Eliminatory; Understanding; Ethics: Review with HREC; Review without HREC; Not discussed;
### D. External Validity

The limitations in study populations connect to the matter of external or rather global validity. External validity is an important parameter to be evaluated to understand the generalizability of results. To ensure external validity in quantitative studies, the researchers must restrict claims which cannot be generalized to all end or expert users. This can be due to the interaction of several factors, like participant selection, experimental setting or temporal factors [21]. For qualitative research, generalization has a different meaning. This is because the intent of qualitative inquiry is not to generalize the findings but to understand a phenomenon in its specific context. To ensure replicability in such cases, it is crucial to properly document the data collection and interpretation procedures used.

During our evaluation, we find that a majority of studies in both our samples do mention or discuss the generalizability of their findings (30 for end-user studies and 24 for expert-user studies), usually in the form of stated limitations (marked ●). However, only seven end-user studies and seven expert-user

| Year | Idx. | Ref. | Sample Loc. | Sample Size | Sample Size | Sample Size | Sample Size | Recruitment | Res. Obj. | Research Method | Theory / Framework |
|------|------|------|-------------|-------------|-------------|-------------|-------------|-------------|----------|----------------|-----------------|
| 2008 | NE1  | [45] | Children    | N/A         | Gen. Pub.   | Spec. Users | Sample Loc. | Mixed Method | Exp. Valid. | Lab              | Ethics          |
| 2009 | NE3  | [88] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE4  | [81] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE5  | [78] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
| 2010 | NE6  | [72] | ●           | ○           | ●           | ●           | ●           | ●           | ●         | ●               | ●               |
| 2011 | NE7  | [155] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE8  | [123] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
| 2012 | NE9  | [119] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
| 2013 | NE10 | [117] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
| 2014 | NE12 | [145] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE13 | [9]  | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE14 | [91] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
| 2015 | NE15 | [139] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE16 | [7]  | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE17 | [16] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE18 | [12] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE19 | [71] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
| 2016 | NE20 | [39] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE21 | [87] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE22 | [114] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE23 | [138] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
| 2017 | NE24 | [83] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE25 | [118] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE26 | [137] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE27 | [85] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE28 | [124] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE29 | [154] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE30 | [17] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE31 | [1]  | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
| 2018 | NE32 | [93] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE33 | [110] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE34 | [120] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE35 | [57] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE36 | [580] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE37 | [157] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE38 | [79] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE39 | [105] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE40 | [99] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE41 | [50] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE42 | [123] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE43 | [13] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE44 | [23] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE45 | [116] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE46 | [100] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE47 | [115] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |
|      | NE48 | [84] | ●           | ●           | ○           | ●           | ●           | ●           | ●         | ●               | ●               |

**Legend:**
- **Location:** ○: Western (Europe, North America); ●: Non-Western; □: International (Multiple Regions); No Marker: Unknown;
- **External Validity:** ●: Considered and addressed; ○: Not discussed;
- **Method:** ○: Mixed Methods; ●: Quantitative; □: Qualitative;
- **Theories:** ○: Used; ●: Mentioned; □: Suggested;
- **Grounded Theory:** ○: Full; □: Middleground; □: Analytical;
- **Evaluation of Artifact:** ○: Before and After; ●: Before; □: After;
- **HF Perspective:** ○: Eliminatory; ●: Understanding;
- **Ethics:** ○: Review with HREC; ●: Review without HREC; □: Not discussed.
E. Observations and Recommendations

Key Observations:

We find that population samples are dominated by convenience sampling, that is, in the local environment of the researchers or via their personal contacts. In some cases, we observe Computer Science students being substituted for operators with operational experience [82]. Such limitations are regularly not discussed, or only mentioned as a limitation, while general conclusions are drawn. We tried to be representative by surveying the top security research venues on a global stage.

We found that samples are nearly exclusively sourced from western countries (the U.S., Europe, Australia), without researchers acknowledging that the specific socio-economic background of their population might influence their results.

Key Recommendations: In future research, we, the community, must investigate more diverse population samples in terms of where the sample is located in the world to avoid selection bias. We acknowledge, that this is a hard problem.
However, it is important to have a varied population represented in the top-tier computer security venues. Removing systemic bias within the field is a lengthy process, which cannot be paraphrased in a paragraph. As a point of reference, we recommend a paper by Guillory [56], who takes a stance on systemic racism in AI. Addressing this problem entails a cultural change in hiring researchers, mentoring early career researchers, and international collaboration. Indeed, looking at the surveyed papers, we find that international collaboration with researchers from non-western regions, for example, Sambasivan et al. [120], holds promise for research which allows us to explore and understand the impact of one’s socio-economic background on security behavior. The main point here is not “utilizing” researchers from the global south in the classical post-colonial western modus operandi to “get access to samples otherwise inaccessible,” but instead collaborating with researchers as the peers they are to allow the wider community a better understanding of differences, and shaping technology in a way that enables secure behavior for humans taking their diverse backgrounds into account. This equally pertains to the perspective of hiring and mentoring, or as Guillory phrased it: “While substantial research has shown that diverse teams achieve better performance [...], we reject this predatory view of diversity in which the worth of underrepresented people is tied to their value add to in-group members.” [56]. Especially given the dominance of western economies not only in research, but also the development of tools and technologies, these steps are imperative to build a securely usable digital and global world.

Nevertheless, research on a population from a specific region has independent scientific value. However, if we focus our research on a specific region or socio-economic background, we must report the location of the population along with recruitment method, sample size, demographics and discuss the generalizability of the findings to a specific population. While we see more work acknowledging limitations with regard to their sample population, simply acknowledging the current U.S./western bias is a limitation which we, as a community, must overcome. Furthermore, convenience sampling, which is currently common, must receive more scrutiny to ensure that results generalize outside its narrow scope, for example, beyond the university-attending population (see WEIRD [65]). It is important to place the research in the global context and work towards reducing biased data which can have serious real-world consequences [125]. If this is not feasible due to the constraints of the research project, the researchers must strive to discuss these limitations in terms of the cultural context and generalizability.

Finally, to help the generalizability of the results, we suggest the use of theoretical frameworks. These can be used to inform the research design as well as aid the external validity of the findings. We discuss the use of theories in detail in Section VII.

V. RESEARCH OBJECTIVE

Following, we investigate the research objective of human factors in security research, that is, what researchers are investigating. For an overview of our findings, please see column “Res. Obj.” in Table II and Table III.

A. User Perspective and Exploration

Investigating the perspective of the user is the most common research goal across both expert and end users (see Figure 8). For example, Dietrich et al. investigate system operators’ perspective on security misconfigurations [33]. However, exploratory research is more prevalent for end-user studies, while a stronger emphasis is put on perspective gathering in expert related studies. Note the distinction between exploratory research and research trying to understand users’ perspective: While the former tries explore a new area from an external point of view, the latter strives to describe how a specific user group perceives an issue. Interestingly, earlier work on expert users is dominated by work that evaluates artifacts, while more recent work shifted towards looking at their perspective on specific issues. This is in line with a mechanic in very early research focusing on end users, for example Whitten and Tygar [150], which also started out by evaluating artifacts, and then matured into considering users’ perspectives.

For expert-user literature, a majority of it is concerned with gathering the user perspective and 12 publications are exploratory research. For end-user publications, there is a similar distribution between papers that are gathering the users’ perspective and those that are exploratory. Gathering users’ perspective is common for issues that are prevalent and understudied. Hence, in these cases, perspective gathering research is exploratory by nature.

Compared to expert-user research, slightly more end-user studies are exploratory. This might be the case because enduser research has been more prevalent and expert-user research is only slowly getting traction in the last few years. For both user categories, however, exploration itself is not the sole aim of most research.
B. Evaluation and Rigorous Design

Artifact evaluation is similarly common between end-user and expert-user studies, including the overlap with other research objectives. In both cases, about half of the existing research is solely performing an evaluation study and the remainder overlaps with the other aims.

Most evaluation studies evaluate an existing or new artifact, but not all of them directly evaluate the usability of an artifact. For example, Wermke et al. performed a (non-user) evaluation of a tool to study obfuscation in Android applications [149]. For all evaluation studies, we identify under “Design Eval.” as part of the “Theory/Framework” columns whether the evaluation was purely done to test something after (●) it has been built, if they first collect users’ input to then design an artifact (●), or if they combine both approaches (●). Only two end-user studies and three expert-user studies gather requirements and input before designing an artifact, and later evaluate their artifact against the users again, see Figure 9. A further one end-user study and four expert-user studies gather input from users before designing the artifact without validating the created artifact afterwards, again, see Figure 9. This approach has the disadvantage that users’ requirements are not incorporated in the design process of the artifact, which is problematic because the users’ actual requirements may be different from the imagined user requirements, thus leading to poor artifacts. In industry, most development processes incorporate a user-driven design component, hoping to prevent a requirements mismatch [144].

The information systems community has already recognized the missing rigor in their artifact design and evaluation. To counteract this limitation, they formalized a processes known as “Design Science Research” (e.g., see March and Smith [86] or Hevner et al. [67, 142]). We suggest that studies in computer security that are in fact designing and evaluating an artifact also leverage the Design Science framework [67, 142].

Unfortunately, we could not identify any paper in our sample that explicitly uses the Design Science framework to inform their research.

C. Hypothesis Testing

Other fields, like the social sciences and safety science, regularly use theories as a guiding concept in their research. They employ a body of existing theories to formulate hypothesis that they can then test using appropriate research designs. Of course, there are other ways to create a hypothesis, such as through previous work or through anecdotal evidence. Only eight expert-user studies test a hypothesis, of which only one also uses an existing theory or framework. The remaining ones build hypotheses based on informal observations and related work. For end-user studies, seven papers test hypotheses. In general, work testing hypotheses often overlaps with evaluation and exploratory studies, and only few papers solely focus on testing a hypothesis.

D. Observations and Recommendations

Key Observations: At the moment, research is dominated by exploratory and perspective work, focusing on instances of problems instead of generalizing to a wider societal and organizational setting. Especially considering our earlier observations on recruitment and a geographic bias in current work, this poses a challenge for our field. As a field, we have to move beyond purely observing, and conduct work that systematizes, understands, and proposes solutions to the effects we observe.

Key Recommendations: To accomplish the further maturation of our field, we suggest that researchers who investigate human factors in computer security adopt the concept of theories (see Section VII). Furthermore, we recommend that researchers adopt the formal process of design science [67, 86, 142]. While, technically, some work already follows (parts) of this framework, diligently following it can increase the rigor and
reproducibility in our work. This will allow us to build and refine our understanding, and derive and test solutions from this body of understanding in a structured way.

VI. RESEARCH METHODS

In this section, we analyze the research methods that are used to perform user studies, that is, which research methods are used to investigate users? Research methodologies are usually quantitative (statistical evaluation of large datasets), qualitative (extraction of qualitative insights from data not statistically analyzable), or both (mixed methods). According to Creswell [21], a quantitative approach tests theories by developing hypotheses and collecting data to support or refute the hypotheses. This is done using an experimental design and instrument-based data collection (like a survey) followed by a statistical analysis. The qualitative approach, however, seeks to understand the meaning of certain phenomenon from the views of the participants situated in specific contexts.

For mixed methods research, both approaches are combined, either sequentially (elaborate the findings of one method with another method), concurrent (merging data from both to provide a comprehensive analysis), or transformative (an overarching theoretical lens within a design using both data types) [21].

The column labeled “Research Method” in Table II and Table III holds a summary of our findings. We mark studies using a quantitative approaches (●), those following a qualitative approach (○), and those using mixed methods (●).

In our sample, we find all three research approaches are being used across six common research tools. However, we notice that quantitative methods are sometimes used for qualitative research and vice-versa, for example, by collecting data for statistic analyses in interviews, or by collecting free-text responses in surveys. We also find that there is no consistency in explicitly mentioning the methodology used to inform the research design and select an appropriate research tool.

For expert users, interviews and surveys are the most used research method, while focus groups and naturalistic observations are least used. Intriguingly, especially naturalistic observations do not suffer from a self-reporting bias, as can usually be found in surveys and interviews [112]. For end users, surveys are the most used method, followed by laboratory studies. While only two studies conducted focus groups, none of the end-user studies in our sample have employed naturalistic observation as a research method.

In our analysis, we find that the expert-user research has a slightly and not significantly higher number of qualitative research compared to mixed methods research and quantitative research (15 mixed methods, 15 quantitative, 18 qualitative) while the end-user research has a high number of quantitative research (17 mixed methods, 18 quantitative, 13 qualitative). The research methods used are also dependent on the identified research objectives (see Section V). Research gathering users’ perspectives is mostly qualitative or mixed methods research. Evaluation studies, on the other hand, are mostly quantitative or mixed methods. Studies that test a hypotheses are almost entirely quantitative, as to be expected. Finally, exploratory studies are mostly qualitative or mixed methods.

Hence, our results are in line with our earlier observations on research objectives. With an emphasis on exploratory and perspective gathering research, qualitative methods are common. Quantitative methods are more prevalent in evaluation studies and hypotheses testing. Where as understanding user perspective or performing exploratory research requires qualitative methods, as they are applicable when studying novel phenomenon or explaining social factors and dynamics.

A. Observations and Recommendations

Key Observations: At the moment, the choice of research tools is commonly driven by the ultimate goal of a study, instead of being a result of a reflection on these goals. We also find that naturalistic observations, which, as we mentioned earlier, would be instrumental in understanding secure behavior especially in the day-to-day workings of expert users are not commonly used.

Key Recommendations: We suggest that future research considers the trade-off between a study’s objective and the available tools more carefully. Especially for exploratory work, researchers should consider naturalistic observations and technical measurements of behavior [30] more closely, instead of relying on interviews and surveys, which potentially suffer from a self-reporting bias.

VII. THEORY

The use of theories is a common practice in the social sciences. According to Van de Ven [140], theories explain why something is happening by describing and explaining causal relationships. They help us to see the findings of a particular study as special cases of a more general set of relationships, rather than as isolated pieces of empirical knowledge. These relationships can then be tested and revised by others. Gregor [54] claims that a good theory consists of three elements: (i) Generalization: Abstraction and generalization from one situation to another are key aspects of any theory, (ii) Causality: Causality is the relation between cause and effect, and (iii) Explanation and Prediction: Explanation is closely linked to human understanding, while predictions allow the theory to be tested and used to guide action.

In summary, theories (should) explain why something happens and from this starting point, can be used for prescriptive or design purposes. Theorizing can bring together different understandings of the problem, thereby ensuring that research contributes to a general class of problems and to a broad variety of organizational and societal settings, instead of a single problem instance. Especially the last step is instrumental to generalize results and provide a scientific foundation.

A. Theory Use

We investigate if and how human factors researchers in computer security have used theories. In case the authors did not use an established theory, we survey a list of existing theories to identify applicable ones [19], marked with a ○ in the
tables. The list of theories was compiled by the Communication Science department at the University of Twente in 2003/2004 for students to better understand theoretical frameworks and aid them in choosing one.

We find 20 papers, seven expert-user papers and thirteen end-user papers that actively use a theory to inform their research, which we mark with ● under the theories section. A further three papers on expert users and nine on end users mention theories in the context of their findings, which we mark with ○.

The most commonly used theory is that of mental models, which is being used in six (two expert and four end-user papers) and mentioned in a further three end-user papers. Mental models are used as a tool to study the ways in which users understand and interact with their environments. Furthermore, we find a cluster of three papers focusing on activity theory. Activity Theory is based on the idea that activity is primary [64]. It holds that doing precedes thinking and that goals, images, cognitive models, intentions and abstract notions like “definition” emerge out of people doing things. Apart from these clusters, we find a diverse set of individual theories being used or mentioned in the remaining 26 papers from both samples that use or mention a theory.

We also evaluated the papers to see which theories might have been applicable, based on their research topic. Mental Models are the most commonly applicable theory, applicable to a further 21 papers, ten for expert users and eleven for end users. Sensemaking theory [147] is promising as well, as it would be applicable to 19 expert-user papers, and two more end-user studies. The theory of reasoned action [44] holds promise for two expert-user papers and six end-user papers.

Apart from these three theories, the other theories are only applicable to a limited set of papers, as, for example, activity theory is only applicable to the three papers where it is also being used. There is no one-size-fits-all approach of a set of “best” theories to inform human factors in security research. Instead, we suggest that researchers do not only focus on selecting specific “heavy hitter” theories, but instead refer to a more comprehensive list, such as the one by the University of Twente [19], at the beginning of their research projects.

We find that more than twice as many (15 compared to 7) papers investigating expert users, rather than end users, leverage grounded theory. This is in line with our earlier observation that expert studies primarily focus on exploratory research, such as investigating user perspectives on issues or their work environment, or trying to get a first look at a specific issue. These approaches usually rely on qualitative data and, hence, are amenable to a GT-based methodology.

However, when investigating how GT is being used in the literature, we find that the majority of papers do not use GT to develop a new theory (see column “GT” under “Theory/Framework”). Instead, most studies (10/15 for experts and five/seven for end-user studies) reference GT only for the sake of the coding process, including the calculation of Cohen’s kappa for inter-rater reliability, and rules for establishing

**Figure 10:** Overview of research methods in expert-user (Figure 10a) and end-user papers (Figure 10b). We find a classical distribution of methods (Surveys more quantitative/mixed methods and Interviews more qualitative/mixed methods). In expert-user related research we find focus groups as a common instrument to generate the foundation of a questionnaire.

**Figure 11:** Overview of how Grounded Theory is being used in expert-user (Figure 11a) and end-user papers (Figure 11b). In both samples, the majority of papers claiming to use GT do so analytically, i.e., skip the theory generation step. Note, that GT is far more prominent in explorative research with expert users, but the distribution between papers fully using GT and those only using it for analytical purposes is comparable.

B. Grounded Theory

Grounded Theory (GT), first developed by Corbin and Strauss [20], is a structured method to derive a theory from data, instead of utilizing an existing theory. It is a common method for exploratory research, especially in new and emerging fields, and when using qualitative data sources. We surveyed all papers in our sample on their use of GT, independent from their use of other established theories.

We find that more than twice as many (15 compared to 7) papers investigating expert users, rather than end users, leverage grounded theory. This is in line with our earlier observation that expert studies primarily focus on exploratory research, such as investigating user perspectives on issues or their work environment, or trying to get a first look at a specific issue. These approaches usually rely on qualitative data and, hence, are amenable to a GT-based methodology.

However, when investigating how GT is being used in the literature, we find that the majority of papers do not use GT to develop a new theory (see column “GT” under “Theory/Framework”). Instead, most studies (10/15 for experts and five/seven for end-user studies) reference GT only for the sake of the coding process, including the calculation of Cohen’s kappa for inter-rater reliability, and rules for establishing
saturation. This means that the authors do not follow the full four-step process for GT (open coding, axial coding, selective coding, theory generation) by omitting the last stage. Instead, these publications provide conclusions around an overview of the discovered codes, often connected to specific quotes from the interviews. This form of incompletely applying grounded theory as a method to present raw data and enrich it with statistical information to seemingly reach a higher level of validity is also known issue in other fields, for example, management sciences [129]. We mark these ○ in the tables.

A further three papers on expert users, and one paper for end-users use a middle-ground approach [122]. Instead of generating their own theory from the collected data, they utilize an existing theory to explain their findings obtained by the first three steps of GT, or they adapt an existing theory to synthesize their findings. We mark these ● in the tables. Ultimately, in our sample, only two papers on expert users and one on end users execute all four steps of GT to contribute to the theory corpus in the field, which we mark ●. In general, these findings align with observations of McDonald et al. [89], who found uncertainty in the HCI community on when and how to use indicators like inter-rater reliability and a tendency to “expect” numeric measures to underline a study’s reliability.

C. Observations and Recommendations

Key Observations: At the moment, only a quarter of surveyed human factor papers use theories to guide their research design and result interpretation. While mental models are a common tool to inform research design, we find no other theory that is consistently used across several papers. Theories that are applicable to a wide range of studies, still go unused (Theory of Reasoned Action, Sensemaking Theory). This lack of theory is, from a scientific perspective, concerning. Other authors, for example Muthukrishna and Henrich [94] see one of the causes for the replication crisis in psychology in an inconsistent and not overarching use of theories in the field. Grounded Theory, a technique for generating new theories from data is commonly claimed to be used, yet authors do not leverage its potential to generate theories. Instead, they focus on the analytical aspects of grounded theory to present their data.

Key Recommendations: To mature from this state, we encourage the field to adopt the concept of using and improving existing theories, as well as forming new ones. As already mentioned in Section V, theories can help the field to generalize findings in specific situations and use these generalizations to implement and test improvements to the handling of the human factor in IT security. Given the state of the field, we might indeed be already in a situation similar to the replication crisis of psychology [94]. Grounded Theory, which can be used for this, is already commonly being used, yet not executed fully. Hence, we recommend authors adopt the full four-step approach of GT and start to formulate theories. Given the emerging nature of the field, theories do not yet have to be refined. Instead, we should start into a process of iteratively testing, validating, and improving findings from earlier work. We recommend as further research more replication studies, as well as studies replicating findings in diverging socio-economical backgrounds (see Section IV).

VIII. Ethics

In this section we assess the implementation of ethical considerations in research involving human subjects. Traditionally, this includes whether the study is ethically justifiable, especially in the context of deception studies and whether participants were exposed to unreasonable harm. However, this point usually also includes whether informed consent was correctly obtained, and the general handling of research data, i.e., whether applicable local privacy laws are followed, and if the authors anonymized the data as soon as feasible during the research project.

Hence, for each paper we identify whether ethical considerations were properly discussed and the study has been submitted to an ethics review board2 approval (●), whether the authors evaluate the ethics of their research themselves and discuss their review in the paper (○), or whether ethics are not discussed in the publication (□).

Even in 2018, individual publications still do not involve an ethics committee, but the general trend is towards a thorough consideration of ethical requirements. Despite this positive trend, it appears that papers investigating expert users initially discussed the ethics of their work less consistently. A common issue, leading to authors not involving an ethics committee, are cases where the authors’ ethics committee is not sufficiently equipped to deal with the specific research plan. A classical case of this is the 2015 study of Burnett and Feamster [14], which measures censorship, but does so raising ethical concerns [97]. However, the ethics committee of the researchers’ institution signed off on this work, most likely due to the board being unfamiliar with the ethical implications of research at the intersection of human factors and computer science. Other studies, for example, Dietrich et al. [33], did not involve an ethics committee because their host institutions does not have such an entity.

A. Observations and Recommendations

Key Observations: While the field made significant progress in the inclusion of ethical considerations, some institutions still lack the appropriate research infrastructure. Furthermore, especially for expert-user related work, authors even in 2018, still do not always discuss their work’s ethical implications.

Key Recommendations: Authors should adopt the habit of evaluating the ethical implications of their work. In case no ethics board is available, the Menlo report can provide guidance on how to evaluate the ethical implications of one’s work [34]. When considered for publication, authors should be held to these standards, that is, documenting their efforts in handling ethical implications and subjects data rights should be mandatory. Furthermore, we suggest to address the issue of no capable ethics board being available by introducing a community driven ethics board, capable of reviewing human

2 A common, yet US centric implementation is the well-known Institutional Review Board (IRB)
we do not review all the end-user papers, we review enough with the end-user publications. Therefore, in order to have a 48 papers from the end-user group. These papers were chosen to provide an overview of the research in both user groups.

To gather the overall gist of end-user research and to be able so as to match the number of expert user papers per year. We understand that this is a random selection but we believe it serves our purpose in answering our research question. While we do not review all the end-user papers, we review enough to gather the overall gist of end-user research and to be able to provide an overview of the research in both user groups.

Overall, we systematize a significantly larger body of factors in security studies, for example, by the IEEE and ACM extending their existing bodies.

IX. Limitations

Our literature survey has several limitations. Firstly, We do not take into account the research before 2008.

While a historical perspective going back to the earliest papers nearly 30 years ago might prove useful to understand the origins of the field, a more recent scope is better suited to provide an overview of the state of the art and comprehensive recommendations on how the field can improve further today.

Secondly, instead of searching the standard databases like SCOPUS or Web of Science using particular keywords to find relevant publications, we chose to search all the top-tier computer security venues. We didn’t use any keywords for search but included all the publications from the top-tier venues after 2008. We made this choice so as to showcase the work of top-tier computer security venues in regards to human factor research. We understand that this may exclude notable human factors research from outside these top-tier computer venues but we consider those out of scope as we want to learn what the leading security venues are doing.

Thirdly, after an in-depth review of the 48 expert user publications, we were interested in comparing these publications with the end-user publications. Therefore, in order to have a reasonable number of papers to review, we opted for balancing the two user groups. For this, we used a random sample of 48 papers from the end-user group. These papers were chosen so as to match the number of expert user papers per year. We understand that this is a random selection but we believe it serves our purpose in answering our research question. While we do not review all the end-user papers, we review enough to gather the overall gist of end-user research and to be able to provide an overview of the research in both user groups.

In terms of methodology, population selection and recruitment we find that currently most work is biased towards samples that are locally accessible to researchers. This means that current work is heavily dominated by a U.S. and Europe-centric view (see Section IV). This current focus of samples may lead to a biased perspective of the work we do, only focusing on the needs, expectations, and behavior of citizens of the global north. In the pursuit of diversifying the populations that our field studies, for example, utilizing Cultural Dimensions Theory might prove useful. Similarly, Design Science is a promising framework to formalize the process of designing and evaluating an artifact, that is, starting with requirements gathering from a population, designing it while considering best practices from the literature, and properly evaluating the final artifact.

At the moment human factors research in computer security is still dominated by exploratory and perspective-gathering research (see Section V). Hence, to further advance the field, we suggest to adopt the concept of theorizing from the social sciences and psychology (see Section VII). Only a fraction of the published work leverages theories (see Section VII-A), even though many of these studies could have benefited from including theories, like Mental Models, Sensemaking Theory or the Theory of Reasoned Action.

Current use of theories is either observational, that is, to improve experimental design in case of Mental Models, or
fragmented, not consistently focusing on a specific set of theories. While several recent publications claim to utilize Grounded Theory, we find that work typically does not execute the full process of Grounded Theory, which should culminate in true theorizing. Instead, it is used as an analytical framework to formalize experimental design and the qualitative data analysis process authors conduct (see Section VII-B).

Future research recommendations

Considering our research question and sub-questions, we can make the following recommendations for future research.

Firstly, in addition to preventing human error, we should also try to understand which behavior leads to secure outcomes, and how we can facilitate that behavior. For this, we recommend investigating expert users and their interactions with their environment from different qualitative perspectives. On top of interviews and surveys, we recommend employing different research methods (e.g. naturalistic observations) to study human factors. Secondly, we recommend investigating more diverse population samples and also better discussing the external validity and limitations of the findings with regards to the samples studied. Thirdly, we recommend exploring and using existing theoretical frameworks to inform the research design. Fourthly, we suggest using and improving upon existing theories as well as forming new ones. This will help in generalizing the results. We also recommend more replication studies, specially replicating findings in different socio-economic backgrounds. Lastly, we suggest that researchers should try to evaluate the ethical considerations of their work in human factors research. We also suggest the possibility of creating a community-driven ethics board which can help researchers that do not have an ethics committee available to them.

Our literature review has several limitations, as discussed earlier. We do not claim to have represented the totality of several decades of human factors research, assuming that would even be possible. We do claim to provide a thorough overview of the research on experts in the past decade and a representative view on work on non-expert user populations for the purpose of making a comparison. We suggest extending the scope of the review by diving deeper into various user categories to gather specific insights and by investigating other security venues that were excluded in this study.

Over the past decade, human factors research has been increasingly recognized as a key contribution to the field of computer security. Now, it is time to learn from its own successes and failures as well as observations and experiences from other fields to further mature it during the next decade.

REFERENCES

[1] Ruba Abu-Salma, M. Angela Sasse, Joseph Bonneau, Anastasia Danilova, Alena Naikashina, and Matthew Smith. “Obstacles to the Adoption of Secure Communication Tools”. In: Proceedings of the 38th IEEE Symposium on Security & Privacy (S&P). May 2017, pp. 137–153. DOI: 10.1109/SP.2017.65.

[2] Yasemin Acar, Michael Backes, Sascha Fahl, Simson Garfinkel, Doowon Kim, Michelle L. Mazurek, and Christian Stransky. “Comparing the Usability of Cryptographic APIs”. In: Proceedings of the 38th IEEE Symposium on Security & Privacy (S&P). May 2017, pp. 154–171. DOI: 10.1109/SP.2017.52.

[3] Yasemin Acar, Michael Backes, Sascha Fahl, Doowon Kim, Michelle L. Mazurek, and Christian Stransky. “You Get Where You’re Looking for: The Impact of Information Sources on Code Security”. In: Proceedings of the 37th IEEE Symposium on Security & Privacy (S&P). May 2016, pp. 289–305. DOI: 10.1109/SP.2016.25.

[4] Yasemin Acar, Christian Stransky, Dominik Wermke, Michelle L. Mazurek, and Sascha Fahl. “Security Developer Studies with Github Users: Exploring a Convenience Sample”. In: Proceedings of the 13th Symposium On Usable Privacy and Security (SOUPS). June 2017, pp. 81–95.

[5] David Adams. A Layman’s Introduction to Human Factors in Aircraft Accident and Incident Investigation. June. ATSB, 2006. ISBN: 9781921092749.

[6] Devon Adams, Alseny Bah, Catherine Barwulor, Nureli Musaby, Kadeem Pitkin, and Elissa M. Redmiles. “Ethics Emerging: The Story of Privacy and Security Perceptions in Virtual Reality”. In: Proceedings of the 14th Symposium On Usable Privacy and Security (SOUPS). June 2018, pp. 427–442.

[7] Julio Angulo and Martin Ortlieb. “WTH!!!” Experiences, Reactions, and Expectations Related to Online Privacy Panic Situations”. In: Proceedings of the 11th Symposium On Usable Privacy and Security (SOUPS). July 2015, pp. 19–38.

[8] Hala Assal and Sonia Chiaisson. “Security in the Software Development Lifecycle”. In: Proceedings of the 14th Symposium On Usable Privacy and Security (SOUPS). June 2018, pp. 281–296.

[9] Adam J. Aviv and Dane Fichter. “Understanding Visual Perceptions of Usability and Security of Android’s Graphical Password Pattern”. In: Proceedings of the 30th Annual Computer Security Applications Conference (ACSAC). Dec. 2014, pp. 286–295. DOI: 10.1145/2664243.2664253.

[10] Lujo Bauer, Lorrie Faith Cranor, Robert W. Reeder, Michael K. Reiter, and Kami Vaniea. “Real life challenges in access-control management”. In: Proceedings of the 2009 ACM SIGCHI Conference on Human Factors in Computing Systems (CHI). Apr. 2009, pp. 899–908. DOI: 10.1145/1518701.1518838.

[11] Matthias Beckerle and Leonardo A. Martucci. “Formal Definitions for Usable Access Control Rule Sets from Goals to Metrics”. In: Proceedings of the 9th Symposium On Usable Privacy and Security (SOUPS). July 2013, 2:1–2:11. DOI: 10.1145/2501604.2501606.

[12] Antonio Bianchi, Jacopo Corbetta, Luca Invernizzi, Yanick Fratantonio, Christopher Kruegel, and Giovanni Vigna. “What the App is That? Deception and Countermeasures in the Android User Interface”. In: Proceedings of the 26th IEEE Symposium on Security & Privacy (S&P). May 2016, pp. 931–948. DOI: 10.1109/SP.2015.62.

[13] David Braue. At least 10m records compromised in single Australian data breach despite drop in NDB reports. 2019. URL: https://www.cso.com.au/article/661702/least-10m-records-compromised-single-australian-data-breach-despite-drop-ndb-reports/.

[14] Sam Burnett and Nick Feamster. “Encore: Lightweight measurement of web censorship with cross-origin requests”. In: Proceedings of the 24th ACM SIGCOMM Conference (SIGCOMM). Aug. 2015, pp. 653–667.

[15] John Burnham. Accident prone: a history of technology, psychology, and misfits of the machine age. University of Chicago Press, 2010.

[16] Farah Chanchary and Sonia Chiasson. “User Perceptions of Sharing, Advertising, and Tracking”. In: Proceedings of the 24th ACM SIGCHI Conference on Human Factors in Computing Systems (CHI). Apr. 2015, pp. 329–346. DOI: 10.1145/2664253.

[17] Rahul Chatterjee, Joanne Woodage, Yuval Pnueli, Anusha Chowdhury, and Christian Stransky. “You Get Where You’re Looking for: The Impact of Information Sources on Code Security”. In: Proceedings of the 37th IEEE Symposium on Security & Privacy (S&P). May 2016, pp. 931–948. DOI: 10.1109/SP.2016.25.

[18] Communication Theories. https://www.utwente.nl/en/bms/communicati on-theories/. 2003.
[155] Feng Zhu, Sandra Carpenter, Ajinkya Kulkarni, and Swapna Kolimi. “Reciprocity Attacks”. In: Proceedings of the 7th Symposium On Usable Privacy and Security (SOUPS). July 2011, 9:1–9:14. DOI: 10.1145/2078827.2078839.

[156] Verena Zimmermann and Karen Renaud. “Moving from a ‘human-as-problem’ to a ‘human-as-solution’ cybersecurity mindset”. In: International Journal of Human-Computer Studies 131 (2019), pp. 169–187.

[157] Yixin Zou, Abraham H. Mhaidli, Austin McCall, and Florian Schaub. “‘I’ve Got Nothing to Lose’: Consumers’ Risk Perceptions and Protective Actions After the Equifax Data Breach”. In: Proceedings of the 14th Symposium On Usable Privacy and Security (SOUPS). June 2018, pp. 197–216.