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A Critical Review of Virtual and Extended Reality Immersive Police Training: Application Areas, Benefits & Vulnerabilities

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Abstract

Virtual and Extended Reality (VR/XR) headsets have promised to enhance police training through the delivery of immersive simulations able to be conducted anywhere, anytime. However, little consideration has been given to reviewing the evidenced benefits and potential issues posed by XR police training. In this paper, we summarise the evidenced usage and benefits of XR police training through a formative targeted literature review (n=41 publications). We then reflect on the prospective technical, security, social and legal issues posed by XR police training, identifying four areas where issues or vulnerabilities exist: *training content*, *trainees and trainers*, *systems and devices*, and *state and institutional stakeholders*. We highlight significant concerns around e.g. the validity of training; the psychological impact and risks of trauma; the safety and privacy risks posed to trainees and trainers; and the risks to policing institutions. We aim to encourage end-user communities (e.g. police forces) to more openly reflect on the risks of immersive training, so we can ultimately move towards transparent, validated, trusted training that is evidenced to improve policing outcomes.

CCS Concepts

• **Human-centered computing** → **Virtual reality**; • **Software and its engineering** → **Virtual worlds training simulations**.

Keywords

Police Training, Extended Reality, Virtual Reality

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1 Introduction

Police officers often respond to emergencies, and to do this swiftly and effectively, they must receive prior training. Such training is currently delivered mainly using traditional methods such as modelling and 'role-playing' possible scenarios in the physical world [16]. Whilst these methods offer great insight and provide essential practical and field skills, it can be time-consuming, costly, and laborious to set up scenes that model a real-life scenario in the physical world. The advent of immersive virtual worlds, such as ones experienced in Virtual and Extended Reality (VR/XR), offers great potential to transform police training for emergency responses through their simulation of real-world environments and events.

Thanks to the resurgence of affordable, high-definition consumer VR headsets in particular (e.g. the Meta Quest platform), XR is seeing renewed adoption and interest in immersive training and simulation within both industry and academia for surgery and medical training [71], engineering training [143], social skills development [51] and more. The virtualisation of existing training materials and exercises, enacted on low-cost (£300 upwards) consumer VR headsets and other XR devices enables immersive virtual and augmented training to be repeatably delivered at scale, whilst supporting personnel-led training on-demand anywhere, anytime. XR training offers the most significant prospective benefits where there exist bottlenecks around resource access, for example, due to limited physical facilities restricting training to what is feasible to deliver rather than what is optimal for the skills development of the individual. Policing is no exception, with police services worldwide having pursued the testing and adoption of immersive XR training vigorously. In the last decade, forces across several constabularies in the United Kingdom (UK) have procured or invested in developing training systems, targeting a variety of outcomes - from scenario-based training through building resilience around hate crimes to technical skills development such as firearms training.

Whilst we know much about the benefits of XR training, little consideration has been given towards the problems that adopting such training potentially creates. This paper addresses this gap by identifying and considering the potential issues surrounding the development, adoption, and use of XR-based training methods. First, we summarise the evidenced benefits of using XR training in general. Then, to give an overview of state-of-the-art applications of XR in policing, we provide illustrative examples of how it has been used in the past in England and Wales, and internationally.

This focus allows us to zoom in on the intricacies of a particular jurisdiction[1], especially as policing in the UK is driven by a dedicated Police Digital Service with a corresponding National Policing Digital Strategy [87]. Next, we turn our attention to the training of police officers, and present the findings of a targeted literature review (n=41) where we categorise the different types of police training where XR-methods have been developed and summarise the benefits asserted, identifying a fundamental problem: the limitations of existing evidence. Then, based on a further scoping review, we offer a novel typology for the potential issues that need to be considered and mitigated when adopting XR training for police.

2 The Use of XR in Policing

Traditional methods of practical police training are costly, time-consuming, and challenging to scale in size. For these reasons, they may be less effective and less frequently delivered than is desirable. Extended reality would appear to offer a solution to many of these issues. Previous research has suggested that immersive VR simulation can be an effective training method resulting in improved performance in real environments [138, 144]. Simulations allow participants to learn through active participation and enable learners to reflect on their performance and knowledge [105]. At the same time, participants can safely make errors, limiting mistakes in live operations [103], offering a means to carefully develop competency in a task in a way that "allows trainees to make mistakes, to ask the 'what if?' questions, and to learn and reflect on such situations without risking (...) safety" [11] - giving trainees "permission to fail" [20]. Trainers can control simulated environments while simultaneously evaluating participants' performance [13]. To provide context for our targeted literature review later in the paper, we first discuss the use of XR by police based on news reports, press releases and grey literature - in many cases the only public venues in which the training delivery and materials are discussed.

2.1 XR in Policing in England and Wales

Police services in England and Wales have begun using immersive and non-immersive virtual reality technologies for various functions, mainly focusing on public engagement and outreach. Non-immersive VR usually describes a virtual environment which people can experience through a screen instead of a fully immersive headset (for reference, most computer games today would fall into the non-immersive category). In 2018 West Midlands Police developed an interactive house simulation to educate the public on crime prevention: users logged onto a website and explored the scene of a burglary in 360 degrees from the perspective of a detective to discover clues about how the householder could have kept the burglar out [114]. Two years later the force developed an interactive car park using a 360 camera to educate the public on how to prevent vehicle crime using non-immersive VR [6]. In 2019 Northumbria Police developed VR games to assist the public in identifying vulnerable people in different contexts [130].

[1]Across the UK there are four different legislatures and executives (England, Scotland, Wales and Northern Ireland). Additionally, the UK has a mix of regional and specialist police forces. In England and Wales, there are 43 territorial police forces of varying size. Scotland has a single police force for the entire country (Police Scotland), as does Northern Ireland (PSNI). Due to these devolved structures, we restricted our focus to England and Wales.

Police have also used VR specifically for youth education. West Midlands Police commissioned the production of a virtual reality film in 2021 to educate young people on knife crime. They trialled the film in local schools and Pupil Referral Units (PRUs) [113]. In 2020, Warwickshire police launched a project using individual headsets to show a 360-degree film with young people to discuss underage drinking and personal safety [145]. With funding from the Road Safety Trust, West Mercia Police developed a virtual reality mobile application for 17-25-year-olds to improve their understanding of road safety and develop strategies for managing peer pressure relating to driving [26]. Norfolk Fire and Rescue Service run a similar initiative where they used Samsung Gear VR goggles to deliver a 360-degree "simulated car crash experience" to educate drivers about road safety [98]. VR has also been used in recruitment for the Metropolitan Police Service to test collaboration skills [73].

There are also a small number of cases in England and Wales of using virtual reality for police training. The first such example dates to 2018, when Gwent Police introduced a system to train police officers to deal with domestic abuse cases developed by the private company Virtual Reality Simulation Systems. The system used a purpose-built room termed 'the cave' containing a 280-degree screen to create a fully immersive environment. The pilot programme involved ten scenarios relating to domestic abuse, developed to reflect real-life scenarios [2]. In 2020, Derbyshire Constabulary began using a VR system built by AVRT, a company specialising in VR scenario-based training. The force intended to run 10 to 14 taser training courses in autumn 2020 with the University of Derby to study the system's efficacy. The system used an Oculus/Meta Quest headset and an imitation taser hand controller to simulate different physical environments, which include a knife-wielding assailant [99]. In 2021, Essex Police also trialled the AVRT system for firearms training, including through a free-roam exercise in a large training area across different training scenarios [10].

In 2021, the Greater Manchester Police (GMP) introduced a virtual reality training pilot to help officers understand and empathise with hate crime victims. The training involves three scenarios, delivered via a head-mounted display, involving different types of hate crimes: one around disability, another involving anti-Semitism and misogyny, and a gender-based hate crime. GMP worked with Mother Mountain Productions to develop the training, and the pilot was provided with guidance from relevant stakeholders, including the Proud Trust, the RNIB, the Campaign Against Anti-Semitism, Trans Forum and the Community Safety Trust [8, 139]. The Metropolitan Police Service deployed a similar training system in partnership with Antser in 2021 to better understand domestic violence and its consequences. In the training, officers were placed in two immersive scenarios using a head-mounted display: one from the perspective of a baby in utero, and another illustrating manipulation of police by a perpetrator [14].

2.2 XR in Policing Internationally

XR has been used globally within policing for various purposes, involving the full range of policing activities such as field patrol, crisis response and crime investigation. It is difficult to assess the scale and extent of XR use by police globally, therefore we only provide a small number of illustrative examples in this section. A

common use of virtual reality, particularly in the US, is for firearms training. This training ranges from basic weapons handling, active shooter training [77], to training focusing on armed-response to domestic violence incidents [24]. Many of these simulations focus on de-escalation, and tackling implicit bias [24, 63]. The Culturally Relevant Computing Lab and the National Training Institute on Race and Equity at Morehouse College in the US announced in 2021 a partnership with Google's Jigsaw to create Trainer, a virtual reality platform to train police in de-escalation tactics [81].

Within Europe, a small number of multi-year multistakeholder projects have explored the use of XR for police training. Funded by the European Union's Horizon 2020 research and innovation programme, the *Training Augmented Reality Generalised Environment Toolkit* (TARGET) Project developed applications to train police and other security agents to respond to 'low probability/high impact' events [136]. Their scenarios focused on developing technical, communication and operational management skills, and addressed ethical decision-making [136]. The training content was developed in tandem with end-users of the scenarios, including law-enforcement professionals from six European member states [136]. *SHOTPROS*, funded by Horizon 2020, was a similar project to develop a new police training curriculum and associated VR training solution [3], running from 2019-2022. The VR aspect of the project was focused on developing a simulation that uses psychological and physiological cues in training sessions and guidelines on VR training technologies for law enforcement [118]. SHOTPROS published a set of recommendations for policy-makers when deciding if and how to implement VR training into existing training structures [121, 122] and didactic guidelines for VR police training [120] amongst other research outputs [119].

In summary, while there are many examples of the development and adoption of immersive training for policing, the evidence base for its validity is unclear. Little has been said about the potential issues and vulnerabilities exposed by the use of immersive training, necessitating further critical review.

3 Reviewing XR Training for Police

In this section, we will discuss existing academic literature on the police using XR for training purposes, which we identified in our structured targeted literature review. We used the following search: `("Police Training" AND ("Virtual Reality" OR "Augmented Reality" OR "Extended Reality" OR "Mixed Reality"))` on *Scopus* (n=24), *Web of Science* (n=33), and the *ACM DL* (n=17) (last refresh conducted in late May 2024) with a first pass to identify relevant papers based on titles (excluding any non-peer reviewed outputs such as dissertations/theses), and a second pass based on relevance of abstract to the topic of XR use in police training. This resulted in identifying 41 papers that developed or reflected on XR training applications specifically for police training (see Appendix Table 3). These applications addressed diverse training needs, including judgement and decision-making, motor skills and coordination, and situational awareness. First, we present the different types of training identified and discuss examples for each. Then, we discuss the key benefits outlined in these papers with examples.

3.1 Application Areas

3.1.1 Firearms Training (17 papers, 41%). Multiple papers described VR shooting applications for police training e.g. training using biofeedback [79, 80] , examining decision-making and bias in the use of lethal force [116, 127], instrumenting performance [128, 133], or designing shooting aids [50], in some cases in extreme scenarios e.g. encountering waves of zombies [80] or other gamified action [76]. For example, [68] propose a system that uses interactive video projected onto walls, which users can interact with through two hand-held controllers. [40] developed a more complex application of VR shooting training that uses an HTC Vive headset to help police officers learn use-of-force policies. The officers were placed in a simulation where they had to respond to a domestic disturbance. Participants were scored by their adherence to best practices on using force provided by the Police Executive Research Forum. They found that compared to participants who completed the same scenario with a desktop computer and keyboard, participants in VR experienced a more significant presence, measured by a self-reported survey and physiological effects. [76] examined SurviVR, a VR training simulation for police accessed by a head-mounted display. One of the scenarios considered in this study places the user in the role of an armed police officer and requires the user to approach and apprehend a suspect wielding a knife.

Some shooting applications introduced physiological measurements into the simulation in acknowledgement that physiological regulation is a key aspect of firearms training. [83] developed a firearms VR simulation and measured how users' frontal oscillatory brainwaves and cardiovascular responses were affected by participation. They observed that the simulation difficulty factor led to varying effects on shooting performance, brainwave activity and heart rate. The authors then used this data to specify values of physiological variables that could be utilised to provide real-time changes to a training simulation based on the user's physiological responses during shooting scenarios. [80] deployed a virtual reality application to deliver biofeedback training. Participants were required to control their breathing while engaging in a selective shoot / don't shoot game. The better users of the training controlled their breathing, the less constrained the participant's vision became in order to facilitate accurate responses to in-game demands.

3.1.2 Crisis Training (21 papers, 51%). These typically cover first response both to small-scale encounters with individuals (partly directing use of lethal force towards assailants such as active shooter drills [75] , partly encouraging de-escalation with e.g. vulnerable populations [147] such as individuals under stress or experiencing a mental health crisis [60]) as well as large-scale simulated crisis events [110] such as a terrorist incidents, with simulated firearms "rampage" [86], explosions [132] and other cues designed to invoke stress [39, 74, 76, 88, 117, 141]. [102] developed a simulation to offer Emergency Management Education with the aim of gaining awareness of multi-professional collaboration and increasing skills and confidence when dealing with different possible scenarios. [110] described the AUGGMED (Multi-agent counterterrorist training in mixed reality environments with an automated severe game scenario) project, a simulation developed for law enforcement agencies, paramedics, firefighters and other first responders to train in a single environment simultaneously. The simulation

involved exercises within three settings: a hot bag and explosion at an underground station, a terror attack and fire at a municipal airport, and a combined cyber/terror attack on a port. Another scenario from Medina's aforementioned study of SurviVR is an Active Shooter scenario where users acted as police attempting to locate and apprehend a suspected shooter.

3.1.3 Stop & Search (6 papers, 15%). These cover any simulated stop of members of the public with the intent to search (e.g. for concealed weapons, drugs etc). Papers here used XR to instrument search behaviour [46], train empathy [44] particularly with vulnerable populations [54] and address profiling bias [42, 95] For example, [27] developed VR training on traffic control, where participants were asked to conduct a simulated traffic stop with random variations (e.g. unsecured items, visible weapons).

3.1.4 Interaction Training (12 papers, 29%). This is defined as any scenario-specific training *interactions* outside of the previous categories, such as encounters with members of the public (e.g. addressing unconscious bias and profiling based on race [12], ethnicity [36] or other demographics [54] etc.), equipment (e.g. tactical robots [97]), or the environment (e.g. room search procedures [46]). For example, [97] developed a virtual reality training tool to instruct police officers on interacting with a robot used by the Special Weapons and Tactical Team (SWAT) to investigate and clear a building. Through a head-mounted display, participants could enter virtual environments and practice the robot's operation. [46] developed a VR application to train police in room searching procedures. Participants were trained in and tested on conducting searches of realistic environments generated in a virtual reality environment, accessed via a head-mounted display and two-held controllers.

3.1.5 After-Action Review (5 papers, 12%). The only application category not directly linked to immersive virtual replicas of scenario-based training was after-action review - where applications and dashboards were developed to either support trainer insight & oversight, or support trainer-trainee interactions [50, 56, 85, 133, 148] typically around performance and physiological response to stress.

3.2 Benefits

Nearly all of the identified papers ascribed benefits to the use of VR for police training. While some claims were more frequently repeated across the 41 papers reviewed, the extent and validity of evidence was variable. Seven papers did not refer to empirical evidence; the remaining papers presented findings from evaluations ranging from hundreds of police officers to a handful of students. In the following section, we discuss some common benefits of XR training for police identified and the evidence base for said claims. The evidence base for positive outcomes of using XR training for police officers has rapidly increased in the last few years. However, as we will demonstrate, empirical evidence of benefits compared to real-life training and of skill transfer to real life are still scarce. This is in line with [141], who found in 2023 that there is only limited scientific evidence to justify VR in police training. The findings of this section must also be read in light of the Technology Acceptance Model (TAM) introduced by Davis [34] and its theoretical extension by Venkatesh and Davis [140]. TAM helps describe how users come to accept and use technology and examines the diverse factors that influence their successful implementation, such as a product's perceived usefulness, usage intention, and ease of use. Social influences, like the image of the people using a particular system and how relevant a device is for one's job, also come into play and are echoed in the insights we could derive from our review.

3.2.1 Quality of Learning. 8 papers evidence positive learning outcomes of XR: increased sensitivity towards own behaviour [42], increased knowledge, intrinsic motivation and self-efficacy [69], development of cognitive skills [46], improved knowledge and performance after force training [40], improved breathing control [80], increased performance and recovery after a real-life surveillance task [17], improved de-escalation skills and reduced bias towards mental illness [65], and reduced inclination to select ethnic minority individuals in a stop and search scenario [95]. However, one study found no evidence of an effect on empathy [44], and another found only marginal evidence of improvement in performance after VR-based room search training [46]. When it comes to comparing VR and real-life training in the context of policing, [88] suggest that for VR training to produce desired learning outcomes, stress cues need to be included that mimic the actual environment that police perform in. Evidence presented in 6 papers shows that VR induces stress [39], VR-training can lead to acute stress response during a simulated active shooter scenario [75], scenario-based VR-training can result in acute stress-response similar to that of real-life training [74], full-body avatars can increase stress levels and feelings of threats [29], multi-sensory weather experiences in VR can induce realistic stress in virtual training [134], and that inducing pain in VR increases perceived stress but does not impact presence [58]. 2 papers demonstrate skill/knowledge transfer to real-life scenarios [79, 109]. 10 papers suggest that VR leads to increased knowledge transfer compared to traditional training. Authors attribute this to the increased sense of presence felt in VR compared to traditional forms of training or the enhanced realism of VR training.

However, there is still only limited evidence of whether VR training is comparable or more effective to real-world training as most studies do not or only offer limited empirical evidence of this. [56] suggest that during after-action reviews of training performance, VR is capable of providing insight (such as providing a suspect perspective) that can improve learning efficacy and make such a review less abstract than a verbal one following real-life training. However, this is not evidenced. 3 papers offered some evidence of comparability to other forms of training. In their study of 237 police officers [57] recorded both similar and different responses in VR and real-life but also noted that in some areas VR exceeded real-life training. [110] compare how AUGGMED (a crisis response simulation using a head-mounted display) improved participants' performance. They found that while VR training, or the inclusion of VR training within a mixed real-life VR training package, did enhance participants' performance in training exercises, this improvement was not greater compared to equivalent real-life training. [36] found that VR provides more realistic and engaging training content than smartphones, leading to increased motivation.

3.2.2 Flexibility. 8 papers suggest that VR allows the delivery of reusable training that would be difficult or impossible to arrange in real-life, particularly due to the impracticality of staging them. VR

training can be controlled and permits the reusability of difficult-to-replicate scenarios. VR may also increase the quality of training through the variability of scenarios, for instance, through randomly created items [27], time, location or demographics [110]. VR allows trainers real-time options to individualise training as well as comparability of performance [85]. And dynamically generated training material can be adaptive to individual difficulty [28]. However, no papers we identified directly tested these claims.

3.2.3 Safety. 9 papers list as a benefit of VR training that it was safer than conventional training exercises. It can allow trainees to interact with dangerous tools safely [52], such as explosives. XR training allows the safe inclusion of vulnerable groups, including children and older people. [54] demonstrate that simulations can provide a safer option for practising techniques of interacting with people on the autism spectrum. In a three-year project which included quantitative and qualitative studies as well as field trials [147] found that VR offers the possibility of safe training in a controllable environment for high-risk situations.

3.2.4 Cost-efficiency. 8 papers attribute lower costs to XR training compared to conventional training. The latter often requires trainees to be co-located, creating logistical and financial costs [110] as well as to interact with expensive equipment [52]. Equipment repair may be cheaper in the case of using simulations as well [40]. However, none of the papers identified evaluated this claim.

3.2.5 Other Benefits. 2 papers suggest that simulations in VR can stop overtraining to idiosyncratic elements of a scenario due to the increased possibility of customisation [28] or individualization of training [85]. No paper we identified validated this claim, for example, by comparing the extent to which participants in VR training 'learned to the scenario' compared to those in real-life training. 3 papers note a specific advantage of virtual reality training is that it does not require participants to be co-located, potentially allowing the possibility of multiple organisations to collaborate on training. The feasibility of this was not tested in any of the papers we read. It is also noted that XR-training offers potential for measuring performance and physiological data [117, 141]. 4 papers offered evidence that data can then be used by trainers, for instance, to dynamically manipulate the stress experience [148], as a predictor of team performance [133], to benchmark reaction times and critique decisions of use of lethal force [128], and can lead to reduced reliance on trainers [57]. It is speculated that XR-training compared to real-world training may be more measurable [150]. However, none of the papers we identified demonstrated if and how XR training enabled greater measurement of participants' performance, improvement or other data points. 2 papers demonstrated how VR can be a useful tool in understanding racial bias in the use of lethal force [127] and in shooting scenarios [116]. Finally, one paper suggested that VR allows the possibility to prototype complex innovations in simplified forms. An example of this kind of use was seen in the paper that offered human-computer interaction training for a tactical robot responsible for assisting SWAT teams.

3.3 Vulnerabilities

In our review we found very limited critical discussion or reflection around the safe, ethical use of XR for police training (see Appendix Table 3), with existing literature placing emphasis on the potential benefits and positive aspects, and only few papers giving any significant focus to the concerns e.g. a recent CHI workshop [104], as well as more summative outputs from the large-scale European Horizon 2020 project SHOTPROS [147]. There were a number of common limitations of this pool of evidence, including varying participant numbers and demographics (e.g. small-scale student population evaluations) and limited comparison against real-life training scenarios or evaluation of transfer effects into real-life policing. While many papers we reviewed noted issues, these were mainly lists of limitations of the empirical study described in the respective papers instead of potential problems around the development or deployment of XR-based police training. Given this, we summarise the noted issues and vulnerabilities found that have the most significance and generalisability to the breadth of police training possible, and provide reflection from domain expert co-authors from *technical* (HCI and XR Harms), *security* (international security and emerging technologies), *social* (criminology and policy) and *legal* domains - all with PhDs and multiple years of research experience. Accordingly, we caveat that our reflection is formative and exploratory, intended to provoke consideration of the potential vulnerabilities posed by immersive training and encourage those engaging in this research or utilising immersive training to consider the risks posed as a priority. We understand vulnerabilities as features of XR police training and its wider social and institutional context of application that may result in harm to individuals, groups, or society. We identified four vulnerability themes:

Training Content The XR training application and its interactions, environments, avatars, animations, audio and more - everything that contributes to the immersive experience.

Trainees / Trainers Resulting from trainees interacting with and trainers delivering XR training - encapsulating user errors, as well as misuse and abuse of materials and data.

Systems and Devices Security of the application, platform and devices (local and cloud) involved in storing training materials, training delivery, or handling training data.

State and Institutional Stakeholders Those that procure, deliver, validate and govern XR training, whose decisions and biases ultimately direct the scope of training.

These themes (see Table 1 for an overview) spanned the lifecyle of conceptualizing, developing and delivering immersive training software (see Table 2), underlining the need to consider vulnerabilities from a multi-disciplinary perspective. For brevity, we summarise a subset of the issues that can emerge in each area.

3.3.1 Training Content.

Validity of Training. As we demonstrated by assessing the commonly referenced benefits of immersive training for police, there is still a significant lack of evidence around skill transfer and comparison with traditional training methods. As such, training may be conceived without a sufficient evidence base or rationale regarding what should be simulated and trained, without clearly described and assessable Intended Learning Outcomes (ILOs) around the purpose of the training, and without an appreciation as to whether XR simulation is appropriate. Key questions around the latter issue include whether XR can feasibly and measurably approximate the

proposed scenario or task and whether there is a rationale for why XR is likely to improve upon the status quo.

The impact of early failures to specify and understand what training is required carries an increased potential likelihood of determining training requirements that are inadequate or inappropriate and do not meet the anticipated needs of the police. This could result in *economic harm* (costs incurred from procuring unhelpful training, underestimates of development costs, etc.) as well as later *pedagogical harm* (users do not learn from training). A concept based on flawed requirements capture or a general lack of existing real-world training to transpose to XR means that there is a risk that the XR simulation being developed will not represent the real-world scenario or task sufficiently.

A valid XR simulation should provide a multi-sensory experience that "closely approximates the characteristics of the environment in which the task eventually will be performed", able to "mimic visual-spatial and real-time characteristics of the task" [111]. Not being able to simulate real life tasks, such as putting handcuffs on [74], as well as using teleportation locomotion [69], and technological difficulties of tracking [86] can undermine validity and can introduce difficulties for participants.

Once developed, a need remains to systematically assess the training tool to validate the transfer of skills and whether it achieves the intended aims. Published studies that evaluate VR simulations often focus on "feasibility, reliability or easiness of use", and do not adequately consider validity. This can frequently be ascribed to difficulties in assessment; for example, if training is delivered infrequently and on a small scale, there may be a lack of data to make comparisons to other tools or to monitor and understand longitudinal impact [19]. For example, in a VR-based search training [46] were not able to evidence the transfer of effective gaze-behaviour.

Short-Term Impact of Distressing Content. [72] suggested that Virtual Reality content, in particular, could enable "risky" experiences such as perceptually realistic violence or sex where the "risk" is that the psychological impact of such (particularly emotionally affective) experiences is unknown. Seeing one's virtual body being threatened with a weapon leads to a feeling of real physical threat and the corresponding physiological reaction [55, 96] and causing harm to virtual characters can cause emotional distress [124]. In the arts, work has pushed the boundaries by creating 'confronting' simulations of sexual abuse and violence, with conflicted beliefs regarding whether such experiences can be a cathartic 'useful outlet', or pose a risk to users [135]. This obviously benefits the transfer and application of skills in challenging environments, as the trainee would be better prepared. For example, for surgical simulations, "the emotional impact of VR simulation on self-efficacy is emphasized and appreciated by trainees, as well as the opportunity... to experience human interactions in problematic environments" [19]. However, such high-fidelity interventions are also likely to induce realistic feelings of stress [89] - posing a tension between ecological validity versus stress as a recognized "barrier to learning" [11].

Long-Term Impact of Distressing Content. We do not yet have VR experiences that could be considered truly perceptually real, but VR training can likely reach a degree of realism that reactions (psychological and physiological) will be as if the experience was interpreted as real. Consequently, the experience of these events is likely to be retained - [112] linked VR experiences to more ingrained autobiographical memory than 2D video, and [115] found that VR can lead to false memory acquisition, with XR able to influence memory encoding and retrieval [18].

VR experiences arguably meet the requirements to induce trauma and associated disorders. For example, post-traumatic stress disorder (PTSD) is thought to originate from experiences where a person "witnessed or was confronted with an event(s) that involved actual or threatened death or serious injury or a threat to the physical integrity of self and others" which evoked "intense fear, helplessness, or horror" ([15] via [22]). As such, there is a tension between preparing trainees for difficult, potentially traumatic experiences they will encounter versus exposing them to experiences that will induce trauma without sufficient support, checks, or safeguards. Beyond trauma, adaptations made due to prolonged exposure should also be considered. Exiting VR after prolonged usage has been suggested to pose challenges regarding sensory adaptation and spatial disorientation [59, 125], with the potential to lead to failures to discriminate between the real and unreal [125]. This could be compounded by any experience of desensitisation or normalisation to, or imitative behaviour of, the events being witnessed [66, 125]. How the trainee experiences body ownership in the simulation can also have a lasting psychological impact. Inhabiting taller or more attractive avatars can improve the user's self-esteem, even longer term outside of VR [146]; and while attractive avatars foster positive self-identity, unattractive avatars can also lead to negative self-identity and more permissive attitudes [146].

Breakdowns in Authenticity. A general vulnerability of virtual training simulation is that it may not fully approximate the variety of events and reactions that could be expected in a given scenario - effectively failing to authentically recreate how the scenario would occur in reality. This could lead to incorrect behaviours (e.g. decision making) being adopted by trainees [11].

3.3.2 Trainee & Trainer.

Physical Safety. The role trainees and trainers play in delivering and undertaking the training in a way that ensures safety is vital. Safety requirements may not be followed, deliberately or unknowingly. This can be the result of insufficient training, equipment or organisational support. If disregarded, physical health and safety requirements may become a vulnerability resulting in harm, as outlined by the EU's Horizon 2020 Investigative, Immersive, and Interactive Collaboration Environment (INFINITY) project before [25]. Ignoring comfort and ergonomics limitations [67], which we anticipate will be resolved over time, VR makes trainees vulnerable to physical harm due to the immersive experiences they undertake. Trainers and trainees may not be aware of these short- and long-term medical risks, may not fully understand the consequences or choose to ignore them due to institutional pressures or personal preferences. XR experiences that selectively or entirely occlude reality introduce the risk of physical harm through failures of safety boundaries, reality awareness mechanisms [91] or other safety measures, leading to collisions with real-world objects, users leaving the play area, or mistaking virtual elements as real [92].

Accessibility. XR training, as with much XR content [41], may be poorly adapted to accessibility needs for certain groups [37, 82] and

individual's physical characteristics e.g. failing to take into account minority bodies [41], the impact of gender [126] and so on. This may lead to the delivery of unsafe training for these individuals.

Privacy Risks of Data Captured During Training. XR training may capture a significant amount of data based on the sophisticated available sensing [90] and the instrumented experience (e.g. [133]), which, depending on the retention policy, poses a persistent problem that may lead to institutional and individual harm. Anonymity and unlinkability [35] are of particular concern given that effective training gives trainees "permission to fail". Studies are beginning to demonstrate that biometric data gathered from XR users, including gaze and movement tracking, can be used to identify individuals [53]. By tracking the movements of users throwing balls at a target, [62] demonstrate that individual VR users could be identified in 90% of cases by comparing recorded hand movements to a library of trajectories. Kupin and colleagues consider this an approach for authenticating user identity and preventing tampering in VR environments, particularly in sensitive areas such as military training. On the other hand, this capacity may be considered a particularly pressing privacy concern for trainees in sensitive environments [84]. This illustrates the conflicting privacy/security requirements (i.e., increasing security can produce privacy concerns).

In time, we can expect that seemingly innocuous combinations of captured data could allow a data processor to not just uniquely identify a user, but also unlock information regarding characteristic and protected traits (gender expression, age, sexuality, race, medical conditions etc.) and other personally identifiable information without the trainee's knowledge or consent. Trainees may be unaware of the extent to which data around their activities and reactions are being captured or, indeed, be unaware of how this data may be intended to be further processed or retained. Biometric psychography [48] considers how likes, dislikes and attitudes can be extracted from XR-typical data, effectively compromising mental privacy. This could reveal insights into existing unconscious bias - both beneficial for targeting training to correct said bias, but also potentially dangerous to the trainee that might find themselves undergoing disciplinary action based on such a revelation.

Indeed, [84] discuss the sensitivity of training data for safety-critical occupations as being one of the biggest threats to the use of virtual training environments, considering that police training data in the hands of terrorists could highlight police blind spots to guide the adaptation of terrorist strategy. Consider a leak of training data related to a terrorist attack scenario. Such data may expose "poor" performance that undermines confidence in emergency response services, but may also give potential attackers an advantage in exposing how such responses are coordinated.

The risks regarding captured data can be amplified if organisations choose not to retain training data in anonymized or unlinkable forms. For example, this data could be used not just for training, but also for accredited assessment, performance reviews, demonstration of competency etc. This introduces risks particularly around confidentiality and agency. If data is not securely captured and stored in a way that can be audited, there is a risk of leaks that could undermine the "permission to fail" intent behind training.

3.3.3 *Systems and Devices.*

Privacy Leakage and Data Breaches. Issues may arise from the technical system that is used to deliver the training and to provide additional necessary functions (e.g. storing data). These include the security of data collected during training (as detailed above). Privacy leakage is also a technical vulnerability, particularly given the 'always on' nature of many XR devices (i.e., they have the potential to be recording all the time [123]). This means that data can be gathered even when the user is unaware the system is on [9, 107]. As a result, in addition to accessing data on the system, a hacker may access everything a VR user sees and hears, as well as change their visual world [43, 142]. Sensor data utilised by XR can be used to draw deeply personal inferences beyond the target task (including medical and emotional information), and therefore involves especially sensitive user data and interactions [9].

Unauthorised Edit Access to Training Materials. Unauthorised access [137] is a threat that underpins many potential harms. Consider a simulation of a violent attack where the third party has manipulated the materials so that the attacker is more likely to belong to a particular ethnicity or demographic. This would be a subtle change, trivial to enact given sufficient access, and yet could impact unconscious bias towards people of that ethnicity or demographic over time.

Disruptive Visuals. Given access, an attacker could alter visual feedback (or what a user sees) to a user's headset in an attempt to disrupt or undermine training, or harm the trainee. The trainee is vulnerable to attacks on their senses and perceptions [149]. An attack could aim to cause simulator or motion sickness in users as a result of inducing a degree of sensory mismatch [49, 93]. Visual perturbations in VR are capable of destabilising users [78] and disorientation can cause physical harm if users collide with objects or walls [137]. Physical harm can also be caused by creating sensory overload for users by overlaying the extended environment with bright lights and loud sounds, or stimulating intense tactile perceptions [106]. Similar attacks using internet posts have targeted epilepsy forums to deliberately trigger seizures [101]. Future XR technology, including contact lenses or implanted devices, may be increasingly difficult or impossible to remove easily [94, 106], exascerbating the risks posed by such feedback.

Immersive Attacks Altering Movement, Behaviour, Reality Awareness, and Memory. Virtual environments can be manipulated much more quickly and easily than physical ones, and unlike other media, an attacker can have complete power over the user's environment. The experience of immersion intensifies the physical and psychological consequences of an attack [31]. The potential for behaviour manipulation is intensified by the cognitive plasticity of users which allows integration between the XR environment and the real world [45, 72]. In XR environments, users are easily immersed - they perceive and react to virtual objects as real, perceive other non-VR bystanders through reality awareness mechanisms to maximize presence [91], and assume other users in the shared space experience what they do [66]. These effects can be leveraged by attackers as alterations to the virtual space have real consequences [149].

Studies such as [18, 38, 61, 131] had particular interest in how XR could be exploited for unethical reasons: for example, by manipulating how memory is encoded to introduce bias [18], or by

deliberately provoking the user to be subject to physical harm by manipulating their perception of themselves and their environment [30, 131]. Krauss *et al.* [61] conducted a speculative design study, finding that XR provoked new deceptive designs that leveraged unique XR properties - *perception*, *spatiality*, *physical / virtual barriers* causing discrepancies between real and virtual worlds, and *device sensing*, finding relevant patterns in particular around leveraging immersive properties towards *persuading* and emotional manipulation, *directing attention*, *disguising content*, and *requiring a detour*. And Eghtebas et al. [38] found that risks were posed in particular around situating information alongside existing physical objects, altering perception of surrounding environments, and in personalized attention grabbing measures.

3.3.4 State and Institutional Stakeholders. When XR is used by the police both the state and institutional stakeholders are responsible for ensuring that it is used in a way which is consistent with the goals of policing as well as ethics in liberal democracies. Institutional stakeholders include the police as well as developers, vendors and providers of police training. Measures that can be taken include legislation in relevant areas, guidelines and clear structures of accountability. Whilst this article cannot cover all of these in depth, we highlight some relevant issues here framing these in terms of overarching justice, trust and accountability, and liability.

Justice, Trust and Accountability. Public trust in legal officials, including law enforcement officers – the police - within liberal democracies is paramount in a functioning legal system [47]. The overarching purpose of having a police service is to protect the public by detecting and preventing crime. This duty is established in common law (precedents set by decisions of the courts) and the police have both common law and legislative powers to execute it. The use of police powers [23] must be compatible with human rights and equalities legislation (e.g. Human Rights Act 1998 and Equalities Act 2010; international treaties like the ECHR of which the UK is a member). The public need assurance that their trust is not misplaced. In recent decades a string of illegalities, misconduct and structural racism findings against police forces and individual police officers in various countries, have undermined trust in the police e.g. the Stephen Lawrence Inquiry [32] finding the Metropolitan police force guilty of structural racism; allegations of rape against undercover police [4]; the murder of Sarah Everard by a serving police officer during COVID lockdown [33] and the reaction of the Police to subsequent vigils for the victim [70]; and police brutality causing, and increasing, during Black Lives Matter protests [129].

Any use of XR in training needs to ensure this trust is not further eroded. Trust in this arm of the criminal justice system is one element of the institutional vulnerability raised by using XR. If XR training inadequately prepares officers, or has potential to discriminate against groups of people through its portrayals of perpetrators and victims in XR scenarios, this undermines police integrity and consequently public trust in their ability to fulfil their functions. Society's experience of policing may be undermined by the delivery of flawed or unvalidated XR training that could result in bias – conscious or unconscious - or have little-to-no transfer of training outcomes to practice, not being a good use of taxpayers' money. A lack of standards and coordination across police forces throughout the country harms society. For example, the public in certain areas/regions may receive a lower standard of police care than other places in the country where police force training is of a higher quality. This would have a knock-on reputational impact on the affected police forces and on the services provided to the public. Police forces may fail to adequately manage resources, including failing to coordinate with other police forces. This could negatively impact the training available through XR, resulting in economic harms due to excessive (unshared) costs, as well as social harms.

Liability. Reviewing liability from a UK perspective, no cases have yet been litigated concerning XR use by the police, but claims are bound to arise in the UK and beyond regarding its safety and surveillance capacities. Using the public law 'judicial review' mechanism querying the lawfulness of police behaviour as a public authority [1], courts have criticised relevant police guidance for failing to comply with human rights law, privacy, data collection and protection, when police use technology (see R (Miller) v The College of Policing [7]; R (Bridges) v The Chief Constable of South Wales Police [5]). These cases demonstrate the likelihood of legal requirements for clear non-discriminatory guidance that adequately protects those affected by its use.

Police officers in training and in the field are employees with employment and health and safety law protection. Employees will be vulnerable to exposure to harms through the capture and further processing of personal sensitive information, and/or mental and physical damage because of the virtual training they experience. Awareness of this vulnerability – wider than police training – needs to be borne in mind. XR for training is likely to be sold as packages by developers contracting with police forces through required public procurement mechanisms. The intellectual property in the product is likely to remain with the developer with the contractual terms dictating who bears risks for malfunction. Any contract terms should stipulate which country's laws apply, together with legislative safeguards and regulation including fairness in contractual terms, commercial and industry norms. Claims could also arise through tort law, that is, the law of civil wrongs, through the existence of a duty of care from one party to another leading to negligence claims for personal injury and other damage.

4 Discussion

XR-driven training is seeing renewed interest and accelerated adoption within policing globally, fuelled by benefits such as quality of learning, flexibility, safety, cost-efficiency, personalisation, access and more. However, in this haste to take advantage of XR, in our view this has come at a notable cost. There is a lack of meaningful consideration of the validity of such training, and the risks posed in designing and deploying immersive training without extensive empirical validation, with little public knowledge evidencing that XR training is fit-for-purpose and being designed in ways that do not expose trainers, trainees, the institutions delivering the training, and the wider society experiencing the results of said training to the potential for harm. What public engagement does exist tends to be in the form of positive news articles and announcements, rather than concrete rationale and evidence of efficacy.

We identified four main areas where issues or vulnerabilities exist which map onto the key factors of XR training: *training content*, *trainee / trainers*, *systems and devices*, and *state and institutional*

stakeholders. Across these areas, we highlighted significant concerns around e.g. the validity and efficacy of training; the short- and long-term psychological impact and risks of trauma; the safety and privacy risks posed to trainees and trainers, in particular through data leakage, breaches and immersive attacks; and the risks to the institutions leveraging said training, potentially undermining public trust in said institutions through delivering unvalidated, closed training with a lack of transparency around evaluation of training outcomes, and unclear liability. Given the growing importance of VR-based immersive training, enabling an anywhere/anytime approach to delivering training of increasing plausibility and perceptual and interactional realism, the identified issues raise significant questions about whether immersive training, particularly for police forces, as currently delivered is truly fit-for-purpose.

The main implication of our findings for future research is that since there is currently a lack of a high quality evidence base, there is urgent requirement for experimental research as well as interdisciplinary work to test the assumptions regarding both the supposed benefits and the potential vulnerabilities. Some of the fundamental questions that need more robust evidencing include skill-transfer to real-life scenarios, further understanding of the short-and long-term impact of distressing content on trainees, and most importantly, flexibility and ease compared to real-life training. There is also pressing need for research to assess and address the vulnerabilities identified in this paper. This requires a holistic understanding of XR-supported training which takes into consideration not only technical but also social and legal factors throughout the decision-making process of adoption and use. For instance, securing systems against data leakage (such as of sensitive, biometric data) involves not only technological solutions but also a legal assessment of compliance with existing regulations, putting in place accountability structures in case something goes wrong, as well as assessing the potential social harms of such events.

4.1 Limitations

It should be noted that our review is formative, and not systematic - providing early evidence to the emerging gaps in knowledge and prevalent issues here. However, even from this, it is clear that the validation of XR police training materials (regarding safety, training outcomes, transfer effects, and whether such materials are ultimately fit for purpose) is at times inadequate - often withheld from public scrutiny, if validation is performed at all. The risk is that inappropriate XR training is being designed, developed, and deployed across a breadth of police forces in a partially siloed manner - inhibiting our ability as a field to coalesce on best practice and derive guidance from missteps. In this paper, we have outlined a number of routes by which mistakes could be made in the design and delivery of XR training that could expose vulnerabilities and the potential for harm. But our analysis here is not exhaustive, nor can it be without further published, public, open access insights and datasets (for which *SHOTPROS* made significant strides towards) into the design, development and evaluation of XR police training.

4.2 Recommendations

In addition to awareness of the specific phenomena we discuss in this paper, we propose that organisations proceed towards the adoption of XR guided by a structured approach, that considers vulnerabilities at each stage of the lifecycle of immersive training. Whilst developing this structured approach is a challenge for future work, we have three main recommendations that should be considered as a "quick fix" that could be trivially adopted:

(1) *Participatory design practices should be considered throughout design, evaluation, usage and deployment* - ensuring that a diverse range of views and demographics meaningfully impact immersive training materials to reduce the risks of e.g. developing the wrong training, introducing unconscious bias etc.

(2) *Evidence-based validation should be conducted to confirm these tools are appropriate and meet the desired training and learning outcomes*, reaching equivalence with or surpassing existing training - and such evidence should be made public through open data sets and open access publications - opening such systems and their designs to external scrutiny as an important step towards establishing public trust in the training police receive.

(3) *Continuous evaluation and monitoring / auditing of the training system, and its associated training data, should be undertaken* during deployment. This monitoring should consider whether the training remains fit-for-purpose, that the validated effects transfer to real-life (short term and/or longitudinally), that the delivery of materials has not been altered in such a way as to reduce effectiveness or introduce previously unseen biases, and that there is transparency about how training outcome data is used, to ensure its use is legal, fair and agreed by trainees and trainers alike.

4.3 Conclusion

XR is on its way to become a major asset in police training due to its flexibility, scalability and immersiveness. However, as shown in our paper, its benefits are often described but are not well evidenced and its potential negative consequences are not yet well appreciated. Our findings expand our understanding of the risks posed by XR training and emphasise that those developing, procuring, and delivering XR training need further support in assessing both the benefits and risks of immersive, perceptually realistic training experiences, as well as seeking stringent and extensive validation. In doing so, we aim to provoke further consideration of the risks posed by immersive training, encouraging the research and end-user communities (e.g. police forces) to more openly reflect on the risks posed, so we can ultimately move towards transparent, validated, trusted training that is evidenced to improve policing outcomes. This is so police forces can make the most of this powerful technology without exposing their staff, organisation, or broader society to unnecessary social, technical, or legal vulnerabilities. We argue that further research is urgently needed in this area to fully understand the positive and negative consequences of using XR in the training of police officers.

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A Supplementary Tables

See Table 1 (at-a-glance overview of vulnerability themes identified), Table 2 (issues across lifecycle of XR training) and Table 3 (identified XR police training papers for review) below.

Table 1: Summary of identified vulnerabilities from our critical review of existing immersive police training literature.

Vulnerability Theme	Sub-Theme	Description
Training Content	*Validity of Training*	Lack of evidence around skill transfer in comparison to traditional training; validity and realism (plausibility, experienced presence etc.) of simulation
	Short-Term Impact of Distressing Content	Exposure to "risky" perceptually realistic violent or emotionally impactful experiences could result in immediate distress.
	Long-Term Impact of Distressing Content	Prolonged exposure to "risky" experiences could impact autobiographical memory and induce trauma and associated disorders, problematic sensitization/normalisation, impact self-identity and more.
	Breakdowns in Authenticity	In being unable to approximate real events/reactions in a scenario, this could result in incorrect behaviours being trained (e.g. flawed decision making).
Trainee & Trainer	*Physical Safety*	Physical harms and medical risks exposed by prolonged or unsafe use of XR technology e.g. through failures or absence of safety boundaries, reality awareness mechanisms, collision avoidance mechanisms etc.
	Accessibility	Accounting for minority bodies given the ableist assumptions that XR technology hardware/software tend to make around the degree of bodily involvement users are able to enact.
	Privacy Risks of Data Captured During Training	Extensive training data (biometric/physiological, behavioural etc.) could be used to de-anonymize and identify users and harm mental privacy (e.g. revealing unconscious bias absent consent) posing risks in how this training data informs promotions, disciplinary action etc.; and how malicious actors might leverage data to identify vulnerabilities in response.
Systems & Devices	*Privacy Leakage and Data Breaches*	Malicious actors with access to XR hardware or associated infrastructure (e.g. cloud logging) could access a wealth of data around what the VR/XR user sees, does, reacts. This could inform personal inferences beyond the target task (e.g. medical or psychological information).
	Unauthorised Edit Access to Training Materials	Training materials could be altered to e.g. encourage biased response through changing the ethnicity or demographic of the simulated actors in the scenario.
	Disruptive Visuals	VR training could be undermined, and trainees harmed, through visual and multi-sensory attacks that might destabilize, distract, or trigger or exacerbate existing conditions (e.g. epilepsy).
	Immersive Attacks: Altering Movement, Behaviour, Reality Awareness, Memory	Immersive attacks manipulate some aspect of perception and cognition to enact harm on the VR user e.g. manipulating movement to cause a safety risk, or manipulating how memory is encoded to induce bias.
State & Institutional Stakeholders	*Justice, Trust, Accountability*	A lack of perceived trust or accountability regarding how police are trained undermines public confidence in policing standards.
	Liability	A lack of validation of immersive training exposes forces to liability if officers take incorrect actions based on said training.

Table 2: Considering our identified issues/vulnerabilities regarding immersive police training before, during, and after training - encapsulating the key steps that a client (i.e. those police forces procuring the training) will typically undertake to arrive at the delivery of XR training. This follows a similar development cycle to any other user-facing software product - conceptualization by the client, before going out to tender (if outsourced) [64], followed by a development process encompassing a Software Development Lifecycle (SDLC) model [108].

Lifecycle Stage	Description	Associated Issues
	Before Training	
1: Conceptualization	Initial ideation, identifying need for XR training	State and Institutional Stakeholders
2: Procurement / Tender / Sourcing / Purchase	Identifying who will provide, or build, the required XR training materials, software and hardware	State and Institutional Stakeholders
3: Analysis / Requirements / Design	Covering all steps around requirements capture and stakeholder engagement in identifying the specifications and acceptance criteria for the XR training materials	State and Institutional Stakeholders
4: Development	Where required, development of novel XR training materials, or modification of existing systems to meet the specifications for (3)	Content; Trainer and Trainee; Systems and Devices.
	During Training	
5: Validation / Testing	Evidencing the efficacy of the training materials, and whether they meet the intended learning outcomes and exhibit anticipated transfer effects.	Content; Systems and Devices
6: Delivery	How the XR training materials are delivered to the client such that they are able to deploy them (e.g. onboarding materials, instruction for safe, correct use).	Trainer and Trainee
7: Deployment	Process of deploying software and hardware assets and delivering training to real trainees at scale.	Trainer and Trainee
	After Training	
8: Post-Deployment Activities	e.g. production support, maintenance, modifications, monitoring, archival and eventual disposal of materials and data	Systems and Devices

Table 3: The 41 papers identified in our review.

Ref.	Title	Category	Participants	Key Benefits	Noted Issues / Vulnerabilities / Risks
[27]	A concept of a training environment for police using VR game technology	Interaction Training; Stop & Search	3 police officers	Not validated	
[83]	A Psychophysiological Model of Firearms Training in Police Officers: A Virtual Reality Experiment for Biocybernetic Adaptation	Firearms Training	10 police officers	Physiological response in VR experience differs from resting state, suggesting VR can "train cognitive readiness".	Sample size; sensing limitations; exposure time; perceptual realism of peripherals for simulating guns.
[46]	Assessing the learning and transfer of gaze behaviours in immersive virtual reality	Stop & Search / Interaction Training	54 undergraduates	VR can develop cognitive skills;	Efficient gaze behaviours in VR were not retained in transfer test; unable to evaluate transfer to real world.
[85]	Assist the VR trainer–real-time dashboard and after-action review for police VR training	After-Action Review	2 police trainers and more than 110 police trainees "involved in the research process" - unclear of breakdown across studies.	Gives trainers real-time options to individualize training; allows comparability of performance.	Risk of trainees misusing or misinterpreting data;
[110]	AUGGMED: developing multiplayer serious games technology to enhance first responder training	Firearms / Crisis Training	Not specified	Large scale digital simulation.	Technical challenges (e.g. network capacity); realism and suitability of interactions.
[21]	Breathing Biofeedback for Police Officers in a Stressful Virtual Environment: Challenges and Opportunities	Crisis Training	N/A, review	Can deliver biofeedback under stress to train breathing.	
[74]	Can a Virtual Reality Training Scenario Elicit Similar Stress Response as a Realistic Scenario-Based Training Scenario?	Firearms / Crisis Training	31 participants, college students.	VR SBT induces acute stress response similar to in-person SBT, indicative of exercise being "highly realistic"; cost and logistics benefits of VR over in-person SBT.	Interactional realism e.g. VR unable to simulate haptics of putting handcuffs on.
[56]	Changing perspectives: enhancing learning efficacy with the after-action review in virtual reality training for police	After-Action Review	413 police officers	Improved learning efficacy within VR.	Processing feedback right after high-arousal VR training may be cognitively demanding for trainees; lack of validation of transfer to operational contexts.

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Table 3: The 41 papers identified in our review. (Continued)

Ref.	Title	Category	Participants	Key Benefits	Noted Issues / Vulnerabilities / Risks
[80]	Deep-Breathing Biofeedback Trainability in a Virtual-Reality Action Game: A Single-Case Study with Police Trainers	Firearms Training	9 police officers	8/9 participants had improved breathing control in action (in VR) based on the VR training.	Sample size; generalisability; lack of baseline; lack of non-VR transfer test;
[44]	Dutch Police Officers Changing their Perspective through VR: the Effect on Empathy	Stop & Search	38 voluntary police officers	No evidence of effect on empathy	Sample size; gender bias; demographics of study population (regions that were less multicultural)
[147]	Enhancing operational police training in high stress situations with virtual reality: experiences, tools and guidelines	Firearms / Crisis Training	field trials with 234 active police officers and trainers	Possibility to safely train high-risk situations in controllable and reproducible training environments, include a variety of avatars that would be difficult to use in real-life training (e.g., vulnerable populations or animals) and handle dangerous equipment; haptic props; real-time in-action monitoring.	Users' and psychological well-being; ethics in VR (and scenario) design; user data protection; prevention of possible misuse, abuse or dual use.
[75]	Focus: The Science of Stress: Virtual Reality Based Active Shooter Training Drill Increases Salivary and Subjective Markers of Stress	Firearms / Crisis Training	29 participants, non-police university students	Induces physiological stress response.	Short duration; lack of longitudinal study; non-police participants may exhibit different stress response;
[12]	From simulations to real-world operations: Virtual reality training for reducing racialized police violence	Interaction Training	No validation	Speculation why VR could reduce racialized police violence - fidelity, practice opportunities, cost-effectiveness.	Lack of "any organizational research that has sought to empirically demonstrate the effectiveness of such VR training".
[141]	How Officers Perform and Grow under Stress: Police Training in Virtual Reality	Crisis Training	N/A	Logistical benefits over real SBT; benefits of capturing behavioural and physiological data; high degree of control over experience and stressors;	Limited scientific evidence to justify use in police training; Paucity of evidence that VR training gives "officers the opportunity to perceive relevant information and ignore task-irrelevant stimuli, make decisions based on valid cues, and act out their skills as they would in real-life critical incidents."; need for interactional realism through physical props; unrealistic, delayed interpersonal interactions;

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Table 3: The 41 papers identified in our review. (Continued)

Ref.	Title	Category	Participants	Key Benefits	Noted Issues / Vulnerabilities / Risks
[117]	Immersive virtual reality training module for active shooter events	Firearms / Crisis Training	No validation, design only	Breadth of data collection possible in simulated emergency scenario; lack of exposure of trainees to real-world dangers	
[29]	Impact of full-body avatars in immersive multiplayer virtual reality training for police forces	Firearms / Crisis Training	32 police officers	Full-body avatar/embodiment increases the feeling of a threat and is more realistic.	Fidelity / imprecise reconstruction of user's body movements; interactional realism and lack of haptics.
[52]	Implementation of a speech enabled virtual reality training tool for human-robot interaction	Interaction Training	No evaluation reported.	Removes bottlenecks to training with dangerous or expensive equipment (e.g. robotics).	
[54]	Law enforcement training using simulation for locally customized encounters	Stop & Search / Interaction Training	27 participants, mix of law enforcement experience.	Virtual interactions with people on the autism spectrum allow officers to practice techniques without compromising the health and safety of the communities they serve.'	
[40]	Measuring presence and performance in a virtual reality police use of force training simulation prototype	Interaction Training	21 participants, civilians	Narrative control; enforcement of best practice; presence.	
[128]	Measuring Visual Attention with 360 Degree Video Stimuli in Virtually Immersive Environments: A Case Study of Police Officers' Decisions to Shoot	Firearms Training	18 and 37 participants in different scenarios - all criminal justice majors	Ability to benchmark reaction times/critique decisions in simulated use of lethal force.	
[148]	Mind the Heart: Designing a Stress Dashboard Based on Physiological Data for Training Highly Stressful Situations in Virtual Reality	Crisis Training / After-Action Review	37 police officers	Physiological data can help trainers dynamically manipulate the stress of the experience, and target specific high stress incidents for review.	Data privacy and ethical considerations; impact on training (e.g. due to novelty/unfamiliarity)
[58]	No pain, no gain? The effects of adding a pain stimulus in virtual training for police officers	Firearms / Crisis Training	219 police officers	Inducing pain in the VR experience increased perceived stress but did not impact presence - questioning need for high perceptual realism in VR; VR simulates approximates real physical load;	

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Table 3: The 41 papers identified in our review. (Continued)

Ref.	Title	Category	Participants	Key Benefits	Noted Issues / Vulnerabilities / Risks
[42]	Police handling of hate crime: A pilot project to use VR technology for professional development in sensitizing police officers to the experiences of victims of bias crime in Hamburg	Stop & Search / Interaction Training	25 students in police protection program	VR experience increased sensitivity towards one's own behaviour.	
[69]	Prototyping and testing a virtual reality counterterrorism serious game for active shooting	Firearms / Crisis Training	32 participants (non-police)	VR training increased participants' knowledge, intrinsic motivation, and self-efficacy significantly.	Teleportation locomotion can impact ecological validity; lack of assessment of retention of knowledge; lack of comparison of effectiveness to existing training; sample size; duration of experience; simplicity of portrayed scenarios
[127]	Racial Essentialism and Stress: A Deadly Combination for Prospective Police Officers' Encounters with Black Suspects	Firearms Training	49 White criminal justice majors	Controlled study able to explore impact of racial bias and stress on decisions to use lethal force on black suspects - ordinarily difficult to assess.	Demographics of participants (non-police); external validity due to laboratory setting (e.g. lack of concern about being shot virtually)
[116]	Shooter Bias in Virtual Reality: The Effect of Avatar Race and Socioeconomic Status on Shooting Decisions	Firearms Training	50 participants (members of public)	VR evidenced shooter bias based on race and socialeconomic status - ordinarily difficult to assess.	Need for more data.
[134]	Stress Embodied: Developing Multi-sensory Experiences for VR Police Training	Interaction Training	33 police officers	Multi-sensory experiences of weather in VR can induce realistic stress and enhance realism of virtual training.	
[39]	Stress Inoculation in Police Officers Using Virtual Reality: A Controlled Study	Crisis Training	63 police officers	VR induces stress and can be used as stress inoculation	Diversity of stressors possible in lethal force encounters challenging to replicate
[88]	Stress Out: Translating Real-World Stressors into Audio-Visual Stress Cues in VR for Police Training	Crisis Training	None		Need to examine ecological validity and comparison to real-life baselines.
[36]	Sugarcoating a Bitter Pill - VR Against Police Ethnic Profiling	Interaction Training	103 police offcers	VR created more persuasive, engaging content compared to smartphone training materials, benefitting trainees that may lack motivation to participate.	Lack of evaluation of transfer and longitudinal effects;

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Table 3: The 41 papers identified in our review. (Continued)

Ref.	Title	Category	Participants	Key Benefits	Noted Issues / Vulnerabilities / Risks
[68]	System model for shooting training based on interactive video, three-dimensional computer graphics and laser ray capture	Firearms Training	None	Allows errors without dangerous consequences;	Limitations of CAVE VR (e.g. distance evaluation)
[86]	Tangible Tactical Belt: Haptic Realism for Virtual Reality Police Training	Firearms / Crisis Training	83 Police trainees	Tactical belt with handgun, baton, handcuffs enhanced interactional/haptic realism and immersion.	Need to ensure user safety (e.g. shortening prop baton); technical disturbances to tracking undermining perception of training.
[17]	The effect of virtual reality simulation on police officers' performance and recovery from a real-life surveillance task	Interaction Training	46 police officers	VR preparation increases police performance and recovery	Motion sickness; system errors; novice VR users require additional time/training.
[95]	The Impact of Racist Stereotypes on Dutch Police Officers' Behaviour in Stop-and-Search Scenarios: a Randomized Study with Deepfake Technology in Virtual Reality	Stop & Search	96 police officers	Reduced inclinatin to select ethnic minority individuals.	Sample size; social desirability influencing results;
[132]	Threat assessment in police VR training: multi-sensory cues for situation awareness	Crisis Training	50 police officers	Threat-evoking multisensory stimulii enhances threat assessment and leads to more realistic decision making	Monitoring effect;
[65]	Training police to de-escalate mental health crisis situations: Comparing virtual reality and live-action scenario-based approaches	Interaction Training	63 police officers	Improved de-escalation skills and reduction in bias towards mental illness	Ecological validity of lab environments; sample size; duration of scenario;
[109]	Validating Virtual Reality as an Effective Training Medium in the Security Domain	Interaction Training	80 police officers	Effectiveness of VR training compared to practical training sessions (e.g. improved knowledge).	Sample size; lack of assessment of longitudinal impact/retention of knowledge.
[100]	Virtual reality for law enforcement training: a demonstration and implication for dispatch priming	Crisis Training	77 individuals, 49% in law enforcement	Feasibility of virtual training	Social desirability bias;
[28]	Virtual Reality Simulator for Police Training with AI-Supported Cover Detection	Crisis Training	72 participant police officers and trainees.	Using VR to dynamically generate training materials (e.g. placing assailants in blind spots); adaptive to individual difficulty.	

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Table 3: The 41 papers identified in our review. (Continued)

Ref.	Title	Category	Participants	Key Benefits	Noted Issues / Vulnerabilities / Risks
[57]	Virtual reality training for police officers: a comparison of training responses in VR and real-life training	Crisis Training	237 police officers	VR and real-life training responses different, but some aspects similar (stress, mental effort, HR) or exceed real life; logistical benefits of VR training; reduced reliance of trainer through AI support based on VR behavioural data;	False positives in scenario;
[133]	xHits: An Automatic Team Performance Metric for VR Police Training	Crisis Training / Firearms Training / After-Action Review	81 police officers	VR can benchmark metrics that are good predictors of team performance	Performance metrics often highly context/scenario dependent