The development of visual search behaviours in immersive virtual reality

David J Harris¹, Kyle J Hardcastle², Mark R Wilson¹, Samuel J Vine¹

1: School of Sport and Health Sciences, University of Exeter, Exeter, UK, EX1 2LU
D.J.Harris@exeter.ac.uk, S.J.Vine@exeter.ac.uk, Mark.Wilson@exeter.ac.uk

2: Counter Terrorism Protective Security Operations, Metropolitan Police Service, Lambeth HQ, London, SE1 7LP
Kyle.J.Hardcastle@met.police.uk

Correspondence concerning this article should be addressed to Dr David Harris, School of Sport and Health Sciences, University of Exeter, St Luke's Campus, Exeter, EX1 2LU. Contact: D.J.Harris@exeter.ac.uk

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Abstract

Virtual reality (VR) has clear potential for improving simulation training in many industries. Yet, methods for testing the fidelity, validity and training efficacy of VR environments is, in general, lagging behind their adoption. In this study we examined the effectiveness of VR for training Police room searching procedures, and assessed the corresponding development of perceptual-cognitive expertise through eye-tracking indices of search efficiency. Participants ($n=54$) were assigned to a VR rule-learning and search training game, a search only training game or a no-practice control group. The VR search training group developed more efficient search behaviours (indexed by saccade size, search rate and gaze entropy) and performed better than controls on a novel transfer test. Efficient gaze behaviours learned during training were not, however, evident during the transfer test. These findings demonstrate how VR can be used to develop perceptual-cognitive skills, but also highlight the challenges of achieving transfer of training.

Keywords; fidelity; Police; Policing; training; validity; VR;

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Introduction

Virtual reality (VR) has huge potential for revolutionising training in a number of high-pressure and safety critical environments. Of particular interest is the training of perceptual-cognitive and motor skills, such as those needed in sport (Bird, 2019), surgery (Moglia et al., 2016), aviation (Oberhauser & Dreyer, 2017) or defence and security (Lele, 2013). Ultimately, the success of any form of simulation training is determined by whether practice in the simulation transfers to improvements on the corresponding real-world task (Barnett & Ceci, 2002; Gray, 2019). While there is wider debate in Psychology about how readily skills learned in one context can be transferred to new tasks (Barnett & Ceci, 2002; Sala & Gobet, 2017), the ecological validity of VR (Parsons, 2015) means that the potential for transfer is high. Yet, in order to develop perceptual-cognitive and motor skills in VR, it is necessary to establish that these kinds of skills can actually be developed in VR, as the unusual perceptual characteristics of virtual environments may affect how skills are learned (Harris, Buckingham, et al., 2019a; Harris, Buckingham, Wilson, & Vine, 2019). Few studies have addressed this issue by assessing changes in perceptual-cognitive abilities during virtual training (Gray, 2019; Tirp, Steingröver, Wattie, Baker, & Schorer, 2015). In this study we aimed to explore the development of perceptual-cognitive skill and transfer of training in the context of Police room searching.

Effective simulations, for skills training or psychological experimentation purposes, must have the requisite levels of *fidelity* to create realistic behaviour (Gray, 2019; Harris, Bird, Smart, Wilson, & Vine, 2020; Slater, 2009). Fidelity describes the extent to which the simulation recreates elements of the real task, such as the visual, auditory or haptic information available. Ultimately, if the perceptual input available to the user is the same as (or functionally indistinguishable from) the real skill, then transfer of training is likely. Subtypes of fidelity include physical (visual and auditory realism), psychological (realistic perceptual and cognitive demands) and affective fidelity (realistic emotional responses). In reviewing the use of VR for training perceptual-cognitive skills – abilities such as attention, anticipation and prediction – Gray (2019) identifies psychological fidelity as particularly relevant for transfer of training. Psychological fidelity is the extent to which the VR environment demands the same perceptual information for controlling actions, elicits the same gaze behaviour and places the same cognitive demands on the user as the real

environment. Despite evidence that VR training can transfer to real world skills (Michalski et al., 2019) there has been little examination of how perceptual-cognitive skills develop in VR. One exception is a study by Tirp et al., (2015), who found a development of the gaze behaviour *quiet eye* (Vickers, 2007) to occur during VR dart throwing practice, as well as transfer to improved performance in real dart throwing. If VR training applications cannot create a high degree of psychological fidelity, then transfer of training will be impaired by the lack of perceptual-cognitive skill development (Gray, 2019; Harris, Buckingham, et al., 2019).

In this study we aimed to examine the development of a perceptual-cognitive skill (visual search) and transfer of training in the context of Police room searching. Officers searching a house must identify evidence pertinent to the current investigation as well as be attentive to indicators of other criminal activity. Currently, non-specialist officers are instructed how to recognise indicators of terrorist-related activity using classroom-based exercises. While this approach promotes explicit learning about early indicators of terrorism it does not allow the more active development of procedural knowledge and perceptual-cognitive skill that can be achieved through realistic searching practice (Freeman et al., 2014; Trninic, 2018). An encouraging example of the application of VR simulation to Policing is a training device known as AUGGMED (Automated Serious Game Scenario Generator for Mixed Reality Training). AUGGMED allows Police officers and other first responders to practice decision making under pressure during a multi-user VR simulation of a terrorist attack. Comparison between live exercises and AUGGMED training has suggested similar learning benefits between live and VR training (Saunders, Davey, Bayerl, & Lohrmann, 2019), but the development of perceptual-cognitive skills, like visual search, was not assessed.

The ability to search for a target item amongst other, distracting, stimuli has been extensively studied in lab-based, computerised tests (e.g. see Wolfe, 2010). Typically, these tasks take the form of searching for a simple shape hidden within an array of similar shapes; a letter 'T' hidden amongst letter 'L's. This work has shown that visual search ability can be trained, as participants improve their speed and accuracy over repeated trials, and that expert searchers (e.g. doctors inspecting a scan for a tumour) show advanced search behaviours (Eckstein, 2011; Savelsbergh, Williams, Kamp, & Ward, 2002; Wood, Batt, Appelboom, Harris, & Wilson, 2014). Typically, searchers show changes in eye movements that serve to make their search more efficient, such as making a larger initial saccade after trial onset or

making fewer (but longer duration) fixations (Najemnik & Geisler, 2005). There has been limited work that has looked at real-world visual search because of the inherent messiness of real scenes (Torralba, Oliva, Castelhana, & Henderson, 2006), but the expertise of real world searchers (e.g. airport luggage security) suggests that expertise can be developed. More effective ways to train search skills in an ecologically valid way would be beneficial, not just for Policing, but other settings like airport security or radiology (Biggs, Kramer, & Mitroff, 2018).

The present study

For officers to identify early indicators of radicalisation or terrorism during routine house searches they need 1) knowledge of what to look for, and 2) the ability to perform an effective and thorough search. We developed a searching task in VR that aimed to 1) support the development of task-specific knowledge through gamified learning (Kapp, 2012), and 2) allow practice of the perceptual-cognitive skill of scanning and searching a room. As visual search ability can be trained with simple searching tasks (Sireteanu & Rettenbach, 1995) we developed a realistic but simple search task as a training tool. During the task, the participant is required to search through a number of household items placed on a table, then find and select the target as quickly as possible. We aimed to test whether, through repeated practice, participants showed a development of visual search behaviours, and whether training could transfer to a more complex searching task (moving around and searching a whole room). In addition, we aimed to examine whether a gamified method of acquiring item-specific knowledge (through trial and error) was more beneficial than explicit instruction (akin to existing classroom training).

Hypotheses

It was predicted that active search practice would lead to a development of visual search skills (changes in eye movement behaviours) as well as positive transfer to a more complex task. Additionally, it was predicted that gamified learning about items to search for would further enhance search performance in the transfer task. Specifically, it was hypothesised that:

H₁: Participants trained on the full training tool (search practice plus gamified learning) will show better performance on both the training task and a novel transfer task, when compared to participants given explicit instruction and generic search practice, who would in turn show better search performance than those given explicit instruction only.

H₂: Search training in VR (full training and search training group) will lead to a greater development of visual search skill, measured through eye movement metrics (e.g. search rate, fixation duration, entropy), when compared to controls.

H₃: Visual search skills learned on the simple training task will transfer to the more complex novel search task.

Methods

Participants

54 participants (33 female, mean age=22.6 years, SD=3.9) were recruited via convenience sampling from an undergraduate population (see Table 1 for demographics). Participants were provided with details of the study and gave written consent before testing began. Ethical approval was obtained from the University Departmental Ethics Committee prior to data collection. The only exclusion criteria were severe vision problems which would prevent participants from completing the task (but spectacles would still be worn within the headset). To ensure homogeneity across the training groups a number of baseline demographics were collected (Table 1). In addition to age and gender, participants were asked whether they had used VR before (Yes/No), how frequently they played video games (ranging from 1 [very often] to 5 [never]), and had their vision checked for stereoacuity (Randot test).

Table 1. Demographic information (mean and standard deviation)

	<i>Mean age</i>	<i>% Male</i>	<i>Previous VR use (%)</i>	<i>Video game experience (max 5)</i>	<i>3D vision (max 10)</i>
<i>Training group</i>	22.4(3.6)	28	76	3.3(1.5)	5.6(2.6)
<i>Search group</i>	23.6(4.7)	44	72	4.0(1.0)	6.7(1.6)
<i>Control group</i>	21.7(2.3)	29	73	3.9(0.9)	5.9(2.5)

Design

In line with common practice for evaluating training interventions, we compared the training tool to both an active and a passive control group. The relevant causal contrast (Karlsson & Bergmark, 2015) in this case is training as usual, which is classroom-based instruction. This type of explicit instruction received by Police officers in the classroom was replicated in the passive control group and the search only group (i.e. active control), and was compared to a more implicit, gamified version training (training group). As a result, a mixed design was used, with group (full training, active control, passive control) as a between-subject factor and test (pre versus post intervention) as a within-subject factor. Outcome

measures were performance on the training task and two transfer tasks, plus visual search behaviours.

Tasks and materials

Virtual reality tasks

The virtual environment was programmed using the gaming engine Unity (2018.2.10; Unity technologies, CA) and C#. The VR task was presented using the HTC-Vive (HTC Inc., Taoyuan City, Taiwan), a 6 degrees of freedom VR-system that consists of one head-mounted display and two hand-held controllers. The headset was run on an HP EliteDesk PC with an i7 processor and GeForce GTX Titan V graphics card (NVIDIA Inc., Santa Clara, CA). Gaze behaviour in VR was recorded using the built-in Tobii eye tracker in the HTC Vive. The eye tracker uses binocular dark pupil tracking and samples at 120Hz across the full 110° field of view, to an accuracy of 0.5°. Eye tracking data was accessed using the Tobii Pro software development kit and was converted into fixations using the EYEMMV toolbox for MATLAB (Krassanakis, Filippakopoulou, & Nakos, 2014), which identifies fixations using a spatial dispersion algorithm. Fixation parameters were set to a minimum duration criterion of 100ms and spatial dispersion of 1° of visual angle (Salvucci & Goldberg, 2000).

Full training task

The full training task (Fig. 1a) was based on traditional tests of visual search (Eckstein, 2011; Wolfe, 2010) but adapted into a realistic search activity. Participants were placed in a simulation of a small basement style room (see Fig. 1). In the room was a large table on which were between 9 and 14 household items, such as a can of beans, a cup, a mobile phone and a roll of tape. On each iteration of the task (i.e. each trial) the items were randomly selected and spawned at set locations on the table. Participants were required to locate the target item(s) and select them by making a visual fixation on the desired item while simultaneously squeezing the trigger on the Vive controller handle. Participants could select as many items as they wished on each trial. To end each trial the participant was required to select a button on the wall in front of them using the same method. When the trial ended participants were presented with on-screen feedback about the duration of the trial, how many of the selected items were incorrect, and how many targets they missed.

The underlying task of identifying the correct targets was a rule learning game. Five of the 18 total items were correct targets and 13 were distracters, but the identity of these were initially unknown by the participant who had to deduce them through trial and error. On each trial the number of targets to place in the scene was selected pseudo-randomly from 33

counterbalanced combinations that ensured all possible combinations appeared (so all participants received a similar ‘training dose’). Nine of the possible 13 distracters were also randomly spawned on and placed randomly across the set locations.

Fig 1a and 1b. The full training task (1a; left panel) and active control (1b; right panel). The participant must search for and select the target items as quickly as possible, then end the trial by selecting the button on the wall.

Search only training task

The active control task (Fig. 1b) was designed to provide similar searching practice as the full training tool, but without the gamified learning about specific items. Hence the search only task replaced the household items with cubes of three different sizes and three different materials. Participants had to find and select only the metal boxes. This task placed similar demands on visual search, but without the specific item learning and problem-solving demands.

Computerized 2D visual search task

To test whether the VR search training transferred to improvements on a traditional test of visual search, participants also completed a computerised visual search task (Eckstein, 2011; Wolfe, 2010). This 2D visual search task required participants to identify a target letter ‘T’ in orange colour and regular upright position, presented among other letter ‘T’s of incorrect orientation or colour. Participants were required to press the space bar if the target object appeared, or to withhold if the target object was not present. There were 5, 10, 15, or 20 items in each display array and participants completed 50 arrays (lasting approximately 5 minutes). Performance was indexed through number of mistakes (failure to find the target or

failure to withhold the response) and response time. The visual search task was programmed and completed online using psytoolkit.org (Stoet, 2010, 2017).

Transfer task

The transfer task required a much more active search of a large room, more akin to a real Police house search. The transfer task (Fig. 2) placed the household items at various locations around a room so that the participant had to actively move around the room. Participants navigated the room using a teleport function. Participants were instructed to be thorough but swift, and chose to end each trial when they had conducted a sufficiently thorough search, as real officers would. Items were not placed in the most obvious locations but were not actively obscured behind other objects. Videos of all three tasks are available online: <https://osf.io/5n9j3/>.

Fig 2. The transfer task. Participants were required to search for items located around the garage.

Measures

The Simulation Task Load Index (SIM-TLX)

To assess the level of cognitive demand experienced during the full training task, participants completed the SIM-TLX (Harris, Wilson, & Vine, 2019). The SIM-TLX is an adaptation of the NASA-TLX (Hart & Staveland, 1988) for measuring workload during VR simulations. Following completion of the baseline trials on the training task, participants rated the level of demand they had experienced using nine bipolar workload scales: mental

demands; physical demands; temporal demands; frustration; task complexity; situational stress; distractions; perceptual strain; and task control. For this study we only used the ratings from the 21-point Likert scale, and not the pair-wised comparisons.

Performance

Performance on the training task, search only training task and transfer test were assessed based on number of errors (combined score of incorrectly selected items and missed items) and the time taken to complete the trial.

Eye tracking metrics

Saccade size. Previous examinations of visual search have found that participants develop more efficient visual search behaviours as a result of practice. One such improvement is an increase in the size of saccades. Participants learn to more readily identify targets using peripheral vision and become more proficient at making saccades which are larger and land closer to the target (Eckstein, 2011; Mannan, Pambakian, & Kennard, 2010).

Search rate. Search rate represents the way in which information is extracted from the environment. It is calculated from the number of fixations made, divided by the mean fixation duration (Murray & Janelle, 2003). Search rate has been identified as a characteristic of expertise in tasks like sport (Mann, Williams, Ward, & Janelle, 2007; Savelsbergh et al., 2002) and medical image reading (Gegenfurtner et al., 2019). Search behaviour that uses fewer fixations of longer duration is indicative of a knowledge-driven, top-down, less random search strategy (Gegenfurtner et al., 2019). Search rate was calculated relative to time ((search rate/time)*60) to account for differences in trial duration.

Entropy. In general terms, entropy refers to the uncertainty within a system. When applied to gaze behaviour it can indicate variability or unpredictability of gaze location (Allsop & Gray, 2014; Moore, Harris, Sharpe, Vine, & Wilson, 2019; Vine et al., 2015). We adopted a simple measure of entropy (Shannon entropy) to indicate the variability with which gaze was spread across the visual workspace (the visual scene was split into 16 areas of interest and the probability of fixating each was calculated). Shannon entropy (Shannon, 1948) expresses the information contained within a probability distribution in “bits”. It is calculated from the state space of the system (all possible outcomes) and the relative probabilities of all elements in that state-space. For instance, if gaze location was random and distributed fairly evenly across all possible locations entropy would be high. If it was targeted to particular locations in a predictable manner entropy would be low. The entropy value was calculated as the sum of the logarithm of all probabilities in the given state space, $H_{(x)} =$

– $\sum_{i=1}^n P(x_i) \log_b P(x_i)$ (as in Shannon, 1948). The probability of fixating each location was calculated for each trial, before applying the above formula to those probabilities.

Procedure

Participants attended the lab on two occasions lasting up to an hour each. On the first visit they completed the informed consent form and a stereoacuity vision screening test (Stereo Optical Inc., Chicago, IL, United States). Participants then completed the computerised 2D visual search task, followed by a baseline training task assessment (one familiarisation trial plus 10 test trials). Participants were then randomised to one of the three training conditions. Participants in the full training and search only training then completed three blocks of 33 trials on their assigned training. Participants returned for the second visit after a 3-4 day interval. The two training groups then completed a further three blocks of 33 trials on their assigned training (a total of 198 trials). All three groups then completed 10 trials of the training task and repeated the computerised 2D visual search task. Finally, participants completed 10 repetitions on the novel transfer task (see Fig. 3). The active control group and search training group received explicit instruction about what to search for in both the post-test training task the transfer test, but the full training group did not as they had acquired this knowledge through gamified learning. Pilot testing indicated that most participants in the full training group had deduced the correct targets half-way through their 6 practice blocks.

Fig 3. Schematic representation of the flow of participants through the study.

Data analysis

Data analysis was performed in RStudio v1.0.143 (R Core Team, 2017). Four participants did not return for the second visit (two in the training group and two in the active control group), but were not excluded from the analysis as their baseline data could still be entered into the mixed effects model. Outlying data points (individual trials) more than 3 standard deviations from the mean (Tabachnick & Fidell, 1996) were Winsorized by replacing the extreme raw score with the next most extreme score (Signorell et al., 2018). Data was also checked for skewness and kurtosis. Completion time for the training task and completion time and errors for the transfer task were found to be positively skewed so a transform was applied for analyses. Linear mixed effects models were run to examine the effect of training group (full training, search only training, control) and trial (pre v post) on performance and eye tracking measures using the lme4 package for R (Bates, Mächler, Bolker, & Walker, 2014). In order to determine the best fitting model in each instance we initially fitted a near maximal model (Barr, Levy, Scheepers, & Tily, 2013) – with random effects for group and/or test within the random factor of participant – and then simplified the random effects structure using Principal Components Analysis, as described by Bates, Kliegl, Vasishth, and Baayen (2014). The best fitting model in each instance was chosen by simplifying the structure in line with the number of principal components that contribute to explaining additional variance. Successive models were compared using the Akaike information criterion and likelihood ratio tests. All raw data is freely available from <https://osf.io/5n9j3/>.

Results

SIM-TLX

As in previous work () we first evaluated the VR environment with a descriptive analysis of user's workload. The results (Fig. 4) illustrated that the mental demands and the complexity and frustration arising from the task were moderate¹. As expected, the physical demands of the task were low. Participants also reported that there was little perceptual strain induced by the simulation and that it was easy to control, suggesting that although it was cognitively effortful, the simulation did not impose additional load as a result of difficulties interacting with it.

¹ In the context of the scale maximum of 21.

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310

311 **Fig 4a and 4b.** Violin plots with median (solid line) and inter-quartile range (dashed lines)
 312 (a; left) and radar chart (b; right) of scores on the SIM-TLX.

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314 Training task

315 To assess the effect of training group on training task performance, mixed effects
 316 models were run on completion time (seconds) and errors, with participant as a random factor
 317 and allowing random effects of test. The overall model predicting time to completion had a
 318 total explanatory power (conditional R^2) of 67.06%, in which the fixed effects explained
 319 45.52% of the variance. The model's intercept is at 3.15 (SE = 0.11, 95% CI [2.93, 3.37]).
 320 Within this model the effect of group, $F(2,55)=13.73$, $p<.001$, $\eta_p^2=.025$, and the effect of test
 321 (pre v post), $F(1,52)=170.11$, $p<.001$, $\eta_p^2=.156$, were both significant. The interaction effect
 322 was also significant, $F(2,53)=5.54$, $p=.007$, $\eta_p^2=.010$. Pairwise tests indicated that there were
 323 no group differences at baseline ($ps>.18$). At post-test, both the full training group ($p<.001$)
 324 and the search training group ($p=.01$) outperformed the control group. The full training group
 325 also searched more quickly than the search only group ($p=.01$) (see Fig 5A).

326 The overall model predicting errors had a total explanatory power of 84.17%, in
 327 which the fixed effects explain 68.27% of the variance. The model's intercept is at 0.49 (SE =
 328 0.12, 95% CI [0.26, 0.72]). Within this model, the effect of test was significant,
 329 $F(1,51)=365.46$, $p<.001$, $\eta_p^2=.293$. However, the effect of group, $F(2,52)=1.66$, $p=.20$,
 330 $\eta_p^2=.004$ and the interaction effect, $F(2,54)=1.29$, $p=.28$, $\eta_p^2=.003$, were not significant.

Fig 5a and 5b. Box and whisker plot (with data points) showing performance (completion time) on the training task (a; left) and novel transfer task (b; right).

Computerized transfer test

To test for transfer of training to the 2D visual search task, mixed effects models were run on search time (seconds) and number of errors made, with participant as a random factor. The overall model predicting search rate had a total explanatory power (conditional R^2) of 51.62%, in which the fixed effects explain 12.47% of the variance. The model's intercept is at 928.36 (SE = 40.66, 95% CI [850.27, 1006.94]). Within this model the effect of group, $F(2,47)=3.75, p=.03, \eta_p^2=.101$, and the effect of test, $F(1,45)=6.91, p=.01, \eta_p^2=.093$ are both significant. The interaction was not significant, $F(2,45)=0.04, p=.96, \eta_p^2=.001$. Pairwise tests indicated no significant improvement in any of the three groups, although there was a trend towards an improvement in the training group ($p=.07$), and the search only group. ($p=.08$), but not the control group ($p=.41$) (see Fig 6).

The overall model predicting search errors had a total explanatory power (conditional R^2) of 61.91%, in which the fixed effects explain 2.55% of the variance. The model's intercept is at 0.83 (SE = 0.22, 95% CI [0.41, 1.24]). Within this model, the effect of group was not significant $F(2,51)=0.22, p=.81, \eta_p^2=.007$, the effect of test was not significant, $F(1,49)=0.02, p=.90, \eta_p^2=.000$, and the interaction was not significant, $F(2,49)=2.49, p=.09, \eta_p^2=.076$.

Fig 6. Pre and post raw scores (search time) on computerised visual search task.

Novel transfer test

To compare effect of training group on performance (time and errors) on the novel transfer test, mixed effects models with participant and trial as random factors were run. The overall model predicting completion time had a total explanatory power of 71.44%, in which the fixed effects explain 11.97% of the variance. The model's intercept is at 4.89 (SE = 0.11, 95% CI [4.67, 5.11]). Within this model the effect of group was significant, $F(2,44)=4.96$, $p=.01$, $\eta_p^2=.026$. Bonferroni-holm corrected comparisons indicated that there was no difference between full training and search training groups ($p=.27$). The search group were significantly better than controls ($p=.01$) and the difference between full training and controls was marginal ($p=.058$) (see Fig 5B).

The overall model predicting errors had total explanatory power of 52.60%, in which the fixed effects explain 0.66% of the variance. The model's intercept is at 0.39 (SE = 0.13, 95% CI [0.14, 0.63]). Within this model, the effect of group was not significant, $F(2,44)=0.27$, $p=.76$, $\eta_p^2=.001$.

Gaze parameters

Training. To examine changes in gaze behaviour across training mixed effects models were run on saccade size, mean fixation duration and gaze entropy. The overall model predicting saccade size had a total explanatory power of 15.38%, in which the fixed effects explain 5.43% of the variance (marginal R^2). The model's intercept is at 0.23 (SE = 0.017, 95% CI [0.19, 0.26]). Within this model the effect of group was not significant, $F(2,54)=1.75$, $p=.18$, $\eta_p^2=.004$. However, the effect of test, $F(1,49)=26.07$, $p<.001$, $\eta_p^2=.027$ and the interaction, $F(2,50)=4.71$, $p=.01$, $\eta_p^2=.010$ were both significant. Pairwise

comparisons showed that there were significant increases in saccade size in the training ($p=.01$) and search ($p<.001$) groups, but not controls ($p=.43$).

The overall model predicting search rate had a total explanatory power of 43.13%, in which the fixed effects explain 21.80% of the variance. The model's intercept is at 0.85 (SE = 0.046, 95% CI [0.76, 0.94]). Within this model the effect of test was significant, $F(1,50)=100.28$, $p<.001$, $\eta_p^2=.101$, but the main effect of group, $F(2,58)=1.33$, $p=.27$, $\eta_p^2=.003$ and the interaction were not significant, $F(2,52)=2.00$, $p=.15$, $\eta_p^2=.004$.

The overall model predicting entropy has a total explanatory power of 55.20%, in which the fixed effects explain 7.94% of the variance. The model's intercept is at 1.94 (SE = 0.085, 95% CI [1.78, 2.11]). Within this model the effect of group was not significant, $F(2,56)=2.19$, $p=.122$, $\eta_p^2=.005$, but the effect of test, $F(1,49)=6.19$, $p=.02$, $\eta_p^2=.007$, and the interaction, $F(2,51)=4.75$, $p=.01$, $\eta_p^2=.011$, were both significant. Pairwise contrasts indicated no change in entropy in the control ($p=.40$) or training groups ($p=.50$), but a significant reduction in the search training group ($p=.001$).²

Transfer. To compare the gaze behaviour of the training groups during the novel transfer test a mixed effects model was run. The overall model predicting saccade size had a total explanatory power of 13.71%, in which the fixed effects explain 0.33% of the variance (marginal R^2). The model's intercept is at 0.44 (SE = 0.053, 95% CI [0.33, 0.54]). Within this model the effect of group was not significant, $F(2,48)=0.44$, $p=.65$, $\eta_p^2=.011$.

The overall model predicting search rate had a total explanatory power of 50.81%, in which the fixed effects explain 4.33% of the variance. The model's intercept is at 0.55 (SE = 0.031, 95% CI [0.49, 0.61]). Within this model the effect of group was not significant, $F(2,44)=1.95$, $p=.15$, $\eta_p^2=.010$.

The overall model predicting entropy had a total explanatory power of 35.93%, in which the fixed effects explain 1.55% of the variance. The model's intercept is at 2.42 (SE = 0.050, 95% CI [2.32, 2.52]). Within this model the effect of group was not significant, $F(2,48)=0.95$, $p=.39$.

² Saccade size, search rate and entropy were all significant predictors of completion time during training ($ps<.02$), and entropy and search rate were significant predictors of completion time in the transfer test ($ps<.001$).

Fig 7a and 7b. Correlations of search rate (a; left) and entropy (b; right) with time to completion in novel transfer test

Discussion

The increasing accessibility, and decreasing cost, of commercial VR hardware and software has led to considerable interest in VR as training tool, but the effect of VR training on perceptual-cognitive skills is not well understood. In this study we aimed to test the effectiveness of a VR visual search training device, to explore its potential for training Police house searching. We aimed to establish whether perceptual-cognitive expertise for room searching could be developed in VR, and whether training transferred to a more complex search task. These findings are relevant for developing a better understanding of perceptual-cognitive skill learning in VR, as well as for practical applications of VR.

Our primary prediction, that active search practice would lead to improved performance on the transfer task, was largely supported, but there was no benefit for the full training group over search only training. The search only training group significantly outperformed controls in the novel transfer test ($p=.01$), but the difference between controls and full training was only marginal ($p=.058$). This finding suggests that while active search practice transferred to the novel task, there was no additional benefit from gamified learning about specific items. By contrast, there was no difference between groups in terms of errors committed. As Fig 6 panel D illustrates, participants made few errors in the transfer task (all groups averaged less than 0.5 errors per trial) suggesting that there was a floor effect in this measure. In real-world policing, conducting a search that is both thorough and fast is

important, but the transfer task may not have been sufficiently challenging for us to observe a difference in errors as well as completion time.

As predicted, active search practice (both full and search only training groups) led to changes in gaze behaviour indicative of more efficient search. Following training, all groups showed a decrease in search rate, but only the two active searching groups showed an increase in saccade length and only the search only group showed a decrease in entropy. Few studies have investigated the development of perceptual-cognitive skill in VR, and these findings suggest that, despite potential differences between real and VR environments, visual search behaviours can be learned in VR. This suggests a good degree of psychological fidelity in the VR environment (Harris et al., 2020).

Despite group differences in performance on the transfer task, accompanying differences in gaze behaviour were not evident, so our final hypothesis was not supported. Additionally, there were no group differences present in the computerised visual search task either, suggesting that no generalised improvement in visual search ability occurred. This finding illustrates the challenge of transferring perceptual-cognitive skills to new tasks. Specificity is an important feature of expertise, and the differences between the training and transfer tasks may have prevented any transfer of gaze behaviours (Barnett & Ceci, 2002; Sala & Gobet, 2017). In this instance we assessed transfer from a relatively static searching task to one that required locomotion. In the future, the VR training task may have to be more closely aligned with the target task for transfer of gaze behaviours to occur. The benefit of VR training, however, is that tasks can be designed to closely match the real-world scenario.

Limitations

One limitation of this study is that transfer of training was only assessed in another VR task. The fact that the simple task transferred to a full room search is a promising finding, but transfer of training outside of the virtual world will pose more of a challenge (Barnett & Ceci, 2002). Nonetheless, the primary aim of this study was to demonstrate the potential for developing search skills in VR, which was supported by the eye movement metrics. Further work should see to establish whether the training will transfer to a real-world scene, and if developments in search behaviour can be transferred when the tasks are more closely aligned.

Conclusions

If VR is to fulfil its promise and become a productive training methodology in environments like sport, rehabilitation, and defence and security, environments with high levels of psychological fidelity are required. That is, VR training environments must be capable of developing the cognitive and visuomotor abilities that underpin performance in

these domains. In this study we demonstrated that gaze behaviours indicative of visual search expertise (search rate, saccade size and entropy) could be trained in a virtual environment, but that transfer of these skills to new tasks remains a challenge; even in immersive VR. Nonetheless transfer of training to a more complex and ecologically valid task was achieved. The enhanced realism and immersion provided by VR (Parsons, 2015; Slater, 2009), aligned to the motivational (Allcoat & Mühlénen, 2018; Salar, Arici, Caliklar, & Yilmaz, 2020) and practical benefits, means that VR is set to play a major role in human skills training. Continued testing of psychological fidelity and transfer of training is needed to ensure that adoption of VR training is evidence based.

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Tables

Table 1. Demographic information (mean and standard deviation)

	<i>Mean age</i>	<i>% Male</i>	<i>Previous VR use (%)</i>	<i>Video game experience (max 5)</i>	<i>3D vision (max 10)</i>
<i>Training group</i>	22.4(3.6)	28	76	3.3(1.5)	5.6(2.6)
<i>Search group</i>	23.6(4.7)	44	72	4.0(1.0)	6.7(1.6)
<i>Control group</i>	21.7(2.3)	29	73	3.9(0.9)	5.9(2.5)

Figure Legends

Fig 1a and 1b. The full training task (1a; left panel) and active control (1b; right panel). The participant must search for and select the target items as quickly as possible, then end the trial by selecting the button on the wall.

Fig 2. The transfer task. Participants were required to search for items located around the garage.

Fig 3. Schematic representation of the flow of participants through the study.

Fig 4a and 4b. Violin plots with median (solid line) and inter-quartile range (dashed lines) (a; left) and radar chart (b; right) of scores on the SIM-TLX.

Fig 5a and 5b. Box and whisker plot (with data points) showing performance (completion time) on the training task (a; left) and novel transfer task (b; right).

Fig 6. Pre and post raw scores (search time) on computerised visual search task.

Fig 7a and 7b. Correlations of search rate (a; left) and entropy (b; right) with time to completion in novel transfer test