



# Neighborhood crime reduction interventions and perceived livability: A virtual reality study on fear of crime

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## ARTICLE INFO

### Keywords:

Crime prevention through environmental design  
Fear of crime  
Virtual reality  
Watching Eyes intervention

## ABSTRACT

High levels of Fear of Crime (FOC) are associated with people engaging with their community less, lower use of public spaces, and a general sense of overall anxiety. In short, such fear may reduce the livability of an area. The primary goal of this research was to examine the potential consequences of environmental interventions intended to reduce crime on FOC and perceived livability of the area. Using immersive Virtual Reality (VR) technology, in two studies we examined how environmental interventions in residential neighborhoods influence FOC. In Study 1, we examined how motion-activated, dynamic street lighting and sound may decrease FOC. In Study 2, we applied an adapted ‘watching eyes’ intervention and examined how it may inadvertently *increase* FOC in a neighborhood. In Study 1 the intervention did not affect feelings of safety. In Study 2, the ‘watching eyes’ intervention indirectly increased FOC via feelings of being watched. In the Discussion, we highlight the importance of better understanding the boundary conditions of such environmental interventions.

“The most damaging of the effects of violent crime is fear, and that fear must not be belittled.”

President’s Commission on Law Enforcement and Administration of Justice (1967,3)

## 1. Introduction

Fear of crime (FOC) is an important factor influencing well-being both at the individual and the community level. For example, FOC can lead to anxiety and worry that prevent people from using public facilities (e.g., parks), which can deteriorate physical health (Aletta et al., 2016). Such anxieties can also financially harm communities (e.g., not shopping in areas that are perceived to be dangerous; Sayin et al., 2015). Overall, high levels of FOC may reduce the perceived livability of an area.

The primary goal of the present research was to examine the potential consequences of environmental interventions intended to reduce

crime on FOC and the perceived livability of the area. To achieve this, we conducted two studies using two different environmental interventions. One study examined a novel intervention involving light and sound that dynamically responds to motion, whereas the other study regarded a ‘watching eyes’ intervention, an established intervention to reduce anti-social behavior (Bateson et al., 2006). We hypothesized that while the first intervention would reduce FOC and increase perceived livability of the environment, the watching eyes may inadvertently *increase* FOC. In this research, we harness the power of Virtual Reality (VR) to examine how these interventions influence FOC at the cognitive, emotional, and behavioral levels.

## 2. Theory and background

### 2.1. Lighting

Lighting has not only been observed to be negatively correlated with

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<https://doi.org/10.1016/j.cities.2024.104823>

Received 13 March 2023; Received in revised form 17 January 2024; Accepted 19 January 2024

Available online 6 February 2024

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crime rates (e.g., Xu et al., 2018), but also to be positively correlated with feelings of safety (Green et al., 2015; Johansson et al., 2011; Loewen et al., 1993; Nasar et al., 1993; Nasar & Jones, 1997; Son et al., 2023; Stamps, 2005). The underlying premise is that a well-lit area allows individuals to see approaching danger, harmful situations, and where potential offenders may be hiding (Fisher & May, 2009). This has been termed a ‘fish-bowl’ effect: the feeling that individuals, potential victims or targets, and offenders alike, all become more visible when lighting increases (Ceccato & Nalla, 2020).

Interestingly, some research has suggested that having lighting in the immediate area of the person is more important than well-lit areas ahead of the person. Specifically, Haans and de Kort (2012) demonstrated that individuals walking on a street preferred having light in their immediate surroundings over regular lamp posts that lighten parts of the road. While traditional street lighting may not hold the ability to continually increase illumination and ensure the person always feels like they are walking in a well-lit area, modern technology has allowed for the use of dynamic lighting. Dynamic lighting refers to lumination being triggered or activated through motion. One common example are motion-activated lights around a house to deter burglars. Such lights remove the cover of darkness under which burglars and intruders prefer to operate.

Dynamic street lighting consistently keeps a person in good lighting as well as creating a fish-bowl effect. Increased street light receives regular empirical and political support in regard to reducing crime rates. On average, street lighting appears to reduce fear of crime and/or increase feelings of safety. However, these findings are less-consistent and appear to have boundary conditions in regard to factors such as location (e.g., city versus a neighborhood) and luminosity (Ceccato, 2020; Cozens et al., 2003).

## 2.2. Sound

Sound-based interventions could also influence feelings of safety. Human or radio sounds can enhance the sense of not being alone in a place (Sayin et al., 2015). This feeling of social presence is positively related to feelings of safety because this increases the possibility of receiving help when needed (Biocca et al., 2003; Warr, 1990) and enhances the soothing effect of security (Mikulincer et al., 2003). Biocca et al. (2003) note that social presence does not have to be ‘real’ but can also involve the simulated presence of other human beings. Simulated vocal sounds (human or animal) enhance “the illusion of interaction with a social entity” (Lombard & Ditton, 2006). Using sounds to subtly manipulate an environment, so-called ‘sound-scaping’, has been shown to enhance feelings of safety, well-being, and social security (Ekblom, 1996). Approaching a dynamic sound and being surrounded with sounds might even decrease the levels of FOC. Therefore, as with the dynamic lighting, dynamic sounds can be a valuable contribution to environments to reduce FOC.

## 2.3. Watching Eyes effect

The watching eyes effect refers to the phenomenon that people modify their behavior when a pair of watching eyes is in the immediate environment. The assumption is that when people feel like they are being watched (even if by stylized eyes on a poster), they will modify their behavior to align with societal norms and accepted behavior.<sup>1</sup> Evolutionary psychology posits that to avoid predatory threat, humans have evolved to have gaze detection, i.e., the ability to intuitively recognize eyes in the environment. What originally helped our ancestors avoid threats has set the foundation for what social psychologists refer to

<sup>1</sup> It should be noted that there is some research that states for an effect to occur, a would-be offender must also believe that an observer has the ability to intervene in behavior (e.g., Muth et al., 2017).

as reputational concerns; when a person feels like they are being watched, they will conform to societal norms in order to preserve their reputation and avoid persecution and exclusion (Bateson et al., 2006).

This watching eyes phenomenon has routinely been used as an intervention to reduce antisocial and criminal behavior and increase prosocial behavior (Pfattheicher & Keller, 2015). For example, a simple sign with a pair of glaring eyes and the message, “Cycle Thieves, we are watching you”, reduced cycle thefts in the immediate environment by 65 % (Nettle et al., 2012). More generally, a recent meta-analysis suggested that watching eyes interventions can reduce antisocial behavior by as much as 35 % (Dear et al., 2019).

However, while watching eyes may increase normative behavior it may also have an unintended consequence. Specifically, the direct gaze (staring right at someone) used in successful watching eyes experiments (Manesi et al., 2016) can be perceived as hostile and elicit negative emotions (Panagopoulos & van der Linden, 2016). Importantly, the watching eyes intervention is not precise in who it targets or influences and has the ability to increase reputational concerns and negative affect in anyone that may see the watching eyes. This includes law-abiding citizens who have no intention to break the law or deviate from normative behavior. We suggest that a watching eyes intervention aimed at reducing crime does not only influence motivated offenders, but may also increase negative emotions in law-abiding citizens. For example, an increase in CCTV coverage does not always make an area feel safer, and in some cases can actually increase FOC (Lorenz et al., 2013). While CCTV is not the same as a watching eyes intervention, they share the same underlying mechanisms suggested to change behavior, being under the visual scrutiny of an onlooker (e.g., reputational concerns). Therefore, it needs to be determined if a watching eyes intervention can actually have the negative influence of making the general public feel less safe.

## 3. The present research

Historically, assessing the effectiveness of the interventions aimed at reducing FOC and crime more generally such as those described above required field studies. Such experiments typically do not have access to the researched population and hence tend to be unable to test the subjective perceptions of the population vis-vis the manipulated environments or assess the mechanisms driving their behavior. That is, an intervention may work for the hypothesized reason, but also for other reasons not considered in the research design (Van Gelder, 2023). Unless a researcher approached each person, their thoughts and feelings on the environment remain a black box. Moreover, the literature has, just as for the cognitive and affective dimensions, predominantly used self-reports for the behavioral response dimension as well (with questions like: “are there places in your neighborhood that you tend to avoid in the nightly hours?”).

Here, we harness the power of VR in two studies and investigate how environmental interventions may influence the livability of a neighborhood by examining the level of FOC at the cognitive, emotional, and behavioral level.<sup>2</sup> By using VR, we retain the high degree of realism of a field study and the ability to acquire subjective psychometric data like in a lab experiment as well as behavioral data such as where and how participants move through the virtual environment.

In Study 1, we examine how dynamic, motion-activated street lighting and motion-activated sounds influence FOC. In Study 2, we examine how images of watching eyes influence the level of FOC. Taking

<sup>2</sup> This research is part of a larger research program, The Virtual Burglary Project (VBP). The VBP uses VR technology to examine burglary decision-making and expertise using an ecologically valid sample of offenders. We chose to capitalize on this opportunity to examine the potential unintended consequences of environmental interventions that are routinely used to deter crime.

the above literature into consideration, we hypothesized that the dynamic lighting and sound intervention would decrease the perceived likelihood of victimization (H1, Study 1) and would increase the feelings of safety (H2, Study 1). We further hypothesized that watching eyes would increase the perceived likelihood of victimization (H3, Study 2), decrease the feelings of safety (H4, Study 2); and increase the feelings of being watched (H5, Study 2).

### 3.1. Method

#### 3.1.1. Participants

Participants were actively recruited through the university's website and social media channels, and through in-person distribution of flyers. Participants registered via the university's SONA platform. To be able to participate, participants had to be 18 years of age or older, and not be prone to seizures. Participants were compensated with either course credit or 10 euros.

A total of 88 participants completed all materials. Three participants were excluded from analyses because of severe cyber sickness ( $n = 1$ ) and technical problems ( $n = 2$ ). The final sample consisted of 85 participants ( $N_{\text{experimental}} = 41$ ,  $N_{\text{control}} = 44$ ; 80 % female and 20 % male). Participants were on average 21.1 years old. Most participants were first year students ( $N = 60$ , 71 %); however, some participants were not enrolled at the university ( $N = 7$ ; 8 %).

#### 3.1.2. Procedure

All participants participated in both studies in a single research session. Both studies presented here received ethical approval from Leiden University. After signing up via SONA, participants received a confirmation e-mail and in line with the Leiden University's procedure, were asked to fill out an online COVID-screening the day before participating. Before arrival, participants were randomly assigned to either the experimental condition or the control condition via random sampling in blocks of 3.

At the start of the study, participants were informed about the VR task by reading an information letter. Consenting participants filled out a pre-test questionnaire and were taught how to put on the Head Mounted Display (HMD). In this study we used the HTC Vive Pro Eye.<sup>3</sup> To navigate through the environment participants used a standard game controller. To get used to the game controller and HMD, participants first practiced in a test environment (a large empty space resembling a hangar).

After showing an understanding of the game controller and HMD, participants were placed in the first virtual neighborhood (Study 1) and instructed to explore the area to determine if they would like to live there.<sup>4</sup> Once the participants felt like they had seen enough of the neighborhood, they notified the researcher who stopped the program. Participants took off the HMD and filled out a post-test questionnaire. After completing Study 1, a brief recap of the instructions was given and participants entered the second virtual neighborhood (Study 2) and followed a similar procedure. After exiting the second neighborhood, they filled out the post-questionnaire containing questions about this neighborhood and a final questionnaire regarding the overall VR experience. All measures in Study 2 were identical to those used in Study 1. At the end of the research session, the researcher debriefed the participants.

#### 3.1.3. Study 1 – motion-activated light and sound intervention

The neighborhood in this study was created using the software Unity and was an actual replica of a middle-class neighborhood in the city of Rotterdam, The Netherlands. Fig. 1A provides a top-down view of

neighborhood. The neighborhood included several connected housing blocks, a parking area, sidewalks, dark alleyways between structures, and a small water course. Areas like a main road were visible but not accessible by participants.<sup>5</sup> The inclusion of elements like a sidewalk as well as dark, narrow alleyways, allowed us to create areas that could be perceived as “dangerous” and “non-dangerous”. Thus, the narrow alleyways between houses and the area around the water course were categorized as dangerous because they were dark and isolated from the rest of the neighborhood (Fig. 1B).

To be able to determine the effects of lighting and sound on FOC, street lighting poles were placed throughout the neighborhood (Fig. 2A). For participants in the experimental condition, the street lights were motion-activated. To achieve this, a ‘trigger-zone’ surrounded each individual street light (Fig. 2B). If a participant entered this trigger zone the level of lighting increased. Additionally, the street lighting poles also served as the source of the sounds within this study. As such, as participants approached the light post the sounds were played and increased in audio level as a function of the proximity to the street light (Fig. 2B)<sup>6</sup>

Importantly, participants did not have to be directly approaching the street light itself to activate the lighting or sound. Instead, they simply had to be within the ‘trigger-zone’ around the street light. Thus, participants could be walking by the street light and it would be triggered, as long as they were close enough. Finally, for participants in the control condition, the street lights maintained the same level of luminosity and did not emit any audio.

#### 3.1.4. Study 2 – Watching Eyes

The virtual neighborhood used in this study was different from the one used in Study 1 and has been successfully used in previous VR research (e.g., van Sintemaartensdijk et al., 2021). The neighborhood was created using the software Unity and resembles a typical Dutch middle-class residential area, consisting of several street segments, houses, front and back gardens, dark alleyways, and a small elementary school (Fig. 3A). Similar to Study 1, for Study 2, the alleyways between houses were identified as the dangerous areas (Fig. 3B).

In the experimental condition, five motion-activated LED screens were placed throughout the virtual neighborhood (Fig. 3C). As a participant entered the ‘trigger-zone’ of the LED sign, the sign would illuminate and show a pair of human eyes moving from left, to center, to right. The video was played on a loop until the participant left the ‘trigger-zone’ and the sign darkened again. The message “burglars we are watching” was displayed on the bottom of the sign (Fig. 4A, B). We chose to include this message as it mimics real-life watching eyes interventions that are traditionally accompanied by a message. In addition to the affective element of a direct gaze (i.e., anxiety and fear), we reasoned that including a message that highlights burglars would potentially make participants think burglars operate in the area, increasing their FOC through a cognitive element (i.e., risk of victimization).

For participants in the control condition, no screens, and thus, no watching eyes signs, were present. There were no other differences between the two conditions.

### 3.2. Measures

#### 3.2.1. Primary variables

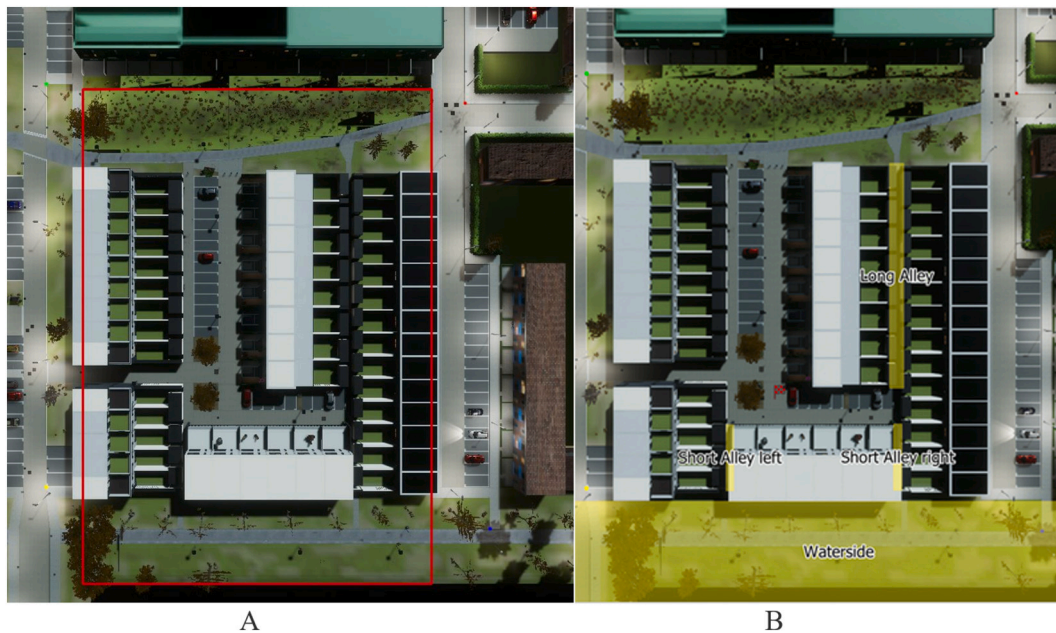
Following the completion of the second virtual neighborhood, participants filled out a post-questionnaire. As stated above, FOC is

<sup>5</sup> The area that could be explored by participants measured approximately  $180 \times 80$  meters.

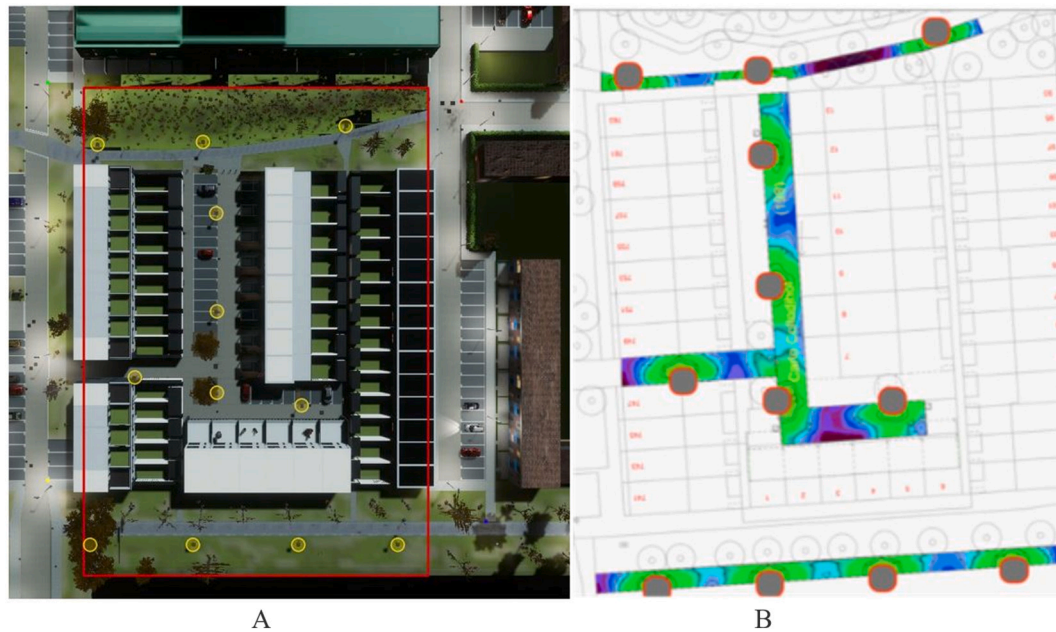
<sup>6</sup> Audio clips played at various street lights included: the sound of a party with various conversations; the sound of a radio being played; and the sound of two cyclists passing and having a conversation.

<sup>3</sup> For a full description of the technical aspects and equipment used in this study please see Supplementary Text A.1.

<sup>4</sup> For full instructions, see Supplementary Text A.2.



**Fig. 1.** Notes: Both images are a top-down view of the virtual neighborhood used in Study 1. In Panel A, the red rectangle outlines the area which participants could explore. Areas outside the red rectangle were not explorable, and objects in this area were placed to make the neighborhood feel more realistic and to provide a backdrop for the explorable area. Although the backyards are visible from the top-down view, these were fenced in and not accessible by participants. In Panel B, the areas highlighted in yellow were deemed to be ‘dangerous’ as they were dark and isolated from the rest of the neighborhood. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



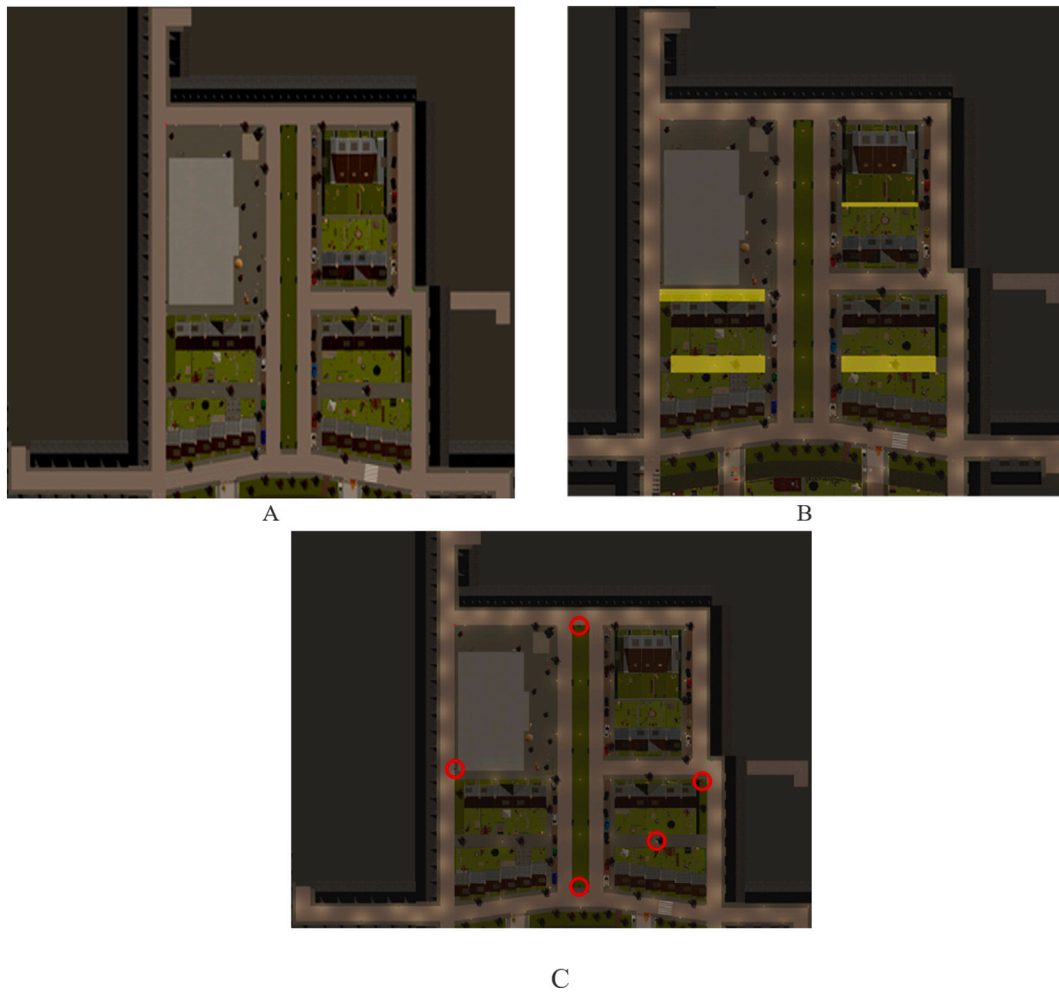
**Fig. 2.** Notes. Image A details the location of the various street lights placed throughout the neighborhood. Image B details the ‘trigger-zone’ for each relative street light. The ‘trigger-zone’ can be read like a heat map, where if a participant is in the green area of the ‘trigger-zone’ the luminosity and audio level will be at its highest. In the dark purple areas of a ‘trigger-zone’, the luminosity and audio level are at their baseline level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

generally considered to consist of three elements, a cognitive appraisal, an affective reaction, and behavior. We believed that the environmental manipulations in each study would influence FOC elements (i.e., the cognitive appraisal and affective reaction), as well as Feelings of Being Watched, which in turn would influence behavior (i.e., avoidant behavior). Fig. 6 details the proposed relationships.

To match our definition of FOC, we broke the elements of FOC into

elements into three measures, risk of victimization, feelings of safety, and behavior.

**Risk of Victimization.** To assess the cognitive element of FOC, we used a measure of the perceived risk of victimization (2012-13 CSEW Technical Report, 2012). The scale is composed of five different crimes: threat, abuse, robbery, assault, and street theft. Participants



**Fig. 3.** Notes: Image A is a top-down view of the virtual neighborhood used in Study 2. Image B denotes the location of the potentially dangerous zones (yellow highlighted areas). Finally, Image C denotes the location of each of the watching eyes signs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

indicated the perceived likelihood of them becoming a victim of each crime in that neighborhood. The perceived likelihood was scored on a 1 (very small) - 7 (very big) scale.

**Feelings of Safety.** To assess the affective element of FOC, we used a measure of feelings of safety (Vanderveen, 2006). Two questions assessed if participants would feel safe walking in the virtual neighborhood alone. Participants answered each question on a 1 (Completely disagree) - 7 (Completely agree) scale.

**Behavioral Measure.** To assess the behavioral element of FOC, we assessed the movement data of the participant in the virtual neighborhood. Movement data refers to all of the spatial data in the virtual environment. For example, it can be the path walked through the virtual environment, the time spent in the environment, and areas (un)explored. We examined if participants differ in the places they do and do not explore based on the experimental condition (e.g., Avoidance Behavior; Rader et al., 2007). For example, participants may not enter the dark alleyway due to poor lighting. This could be interpreted as avoidance behavior. To achieve this, we examine the percentage of walkable area each participant covers during their time in VR.

This measure is created by first identifying the areas in which a participant can walk in each virtual neighborhood. This identified area is then divided into grid cells of three map units. Finally, a data point is created for each participant by counting the number of grid cells entered. Determining if a participant entered a grid cell or not is

achieved by tracking their position in the virtual neighborhood.<sup>7</sup> This is the prevalence of each participant entering cells of approximately 3 map units which are possible to walk on.<sup>8</sup> To illustrate, we have provided a top down image of the neighborhood used in Study 1 (Fig. 5). The entire walkable area has been overlaid with a green grid. Each grid cell is approximately 3 map units. We use the number of grid cells participants entered to determine the percentage of walkable area they covered.

However, VR behavior is difficult to assess because of high levels of variance and heterogeneity (Coffey et al., 2012). Therefore, we don't specify hypotheses for these variables, but simply explore the relationship. In particular, we examine how much participants

<sup>7</sup> This is achieved by logging the x-, y- and z- coordinates at intervals of 1.00 s. From a top-view of the virtual environment, the x-coordinate refers to the position from left to right. The z-coordinate refers to the position from bottom to top. Finally, the y-coordinate represents the height of the headset and is invariant (except from tracking errors) as the participants were sitting throughout the experiment. The scaling was done in map units, where one unit is approximately equal to one meter. When walking straight ahead the distance between the data points was approximately two meters in Study 1 and three meters in Study 2.

<sup>8</sup> By default, a map unity in Unity is one meter. However, through scaling and resizing of objects to ensure a high degree of realism, this may alter slightly. As such, we use the term map unit.



**Fig. 4.** Notes: The images above illustrate the watching eyes intervention placed within the experimental condition of Study 2. In image A, the eyes are looking straight ahead while in image B the eyes have shifted to look to the right. The video also had the eyes looking left. This video was played on repeat until the participant left the ‘trigger-zone’.



**Fig. 5.** Notes: The green grid represents the area in which a participant could walk in the virtual neighborhood. Each grid cell is approximately 3 map units. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

explore: 1) the total walkable area, 2) the walkable area in dangerous zones, and 3) the walkable area in non-dangerous zones. Doing so allows us to draw unique comparisons between conditions regarding the areas (un)explored. As an example, we may expect to see that because the dynamic lighting increases lighting in the dangerous areas, participants in the experimental condition would explore more of the walkable area in dangerous areas compared to participants in the control condition.

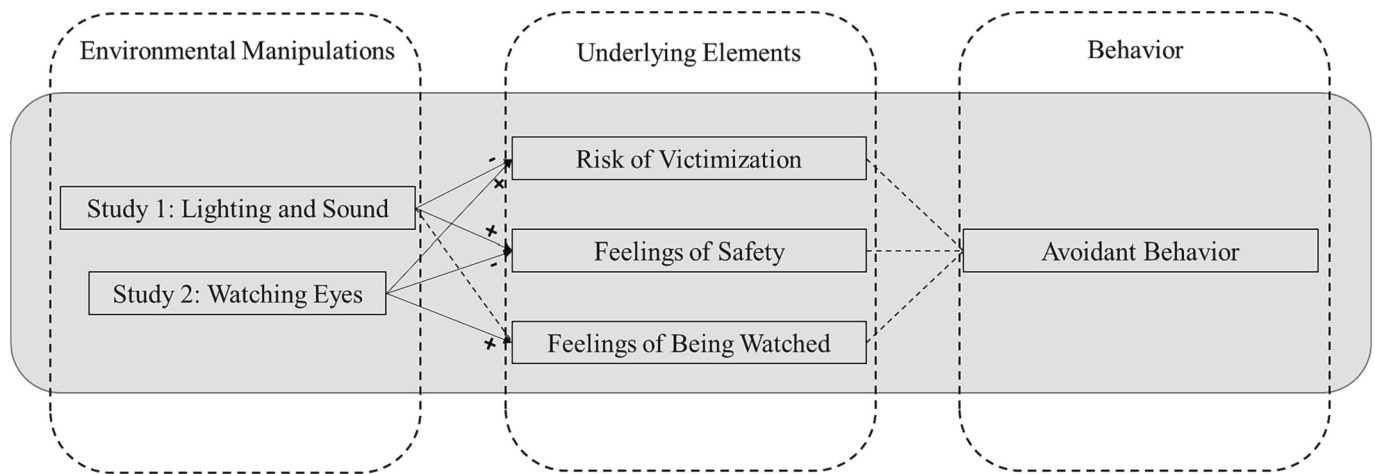
**Feelings of being watched.** Finally, we assessed if participants felt like they were being watched. As discussed in Section 2.3, this can give rise to negative emotions such as anxiousness, which may in turn decrease feelings of safety. Two questions on a 1 (Completely disagree) - 7 (Completely agree) Likert scale asked if participants felt watched.

### 3.2.2. Control measures

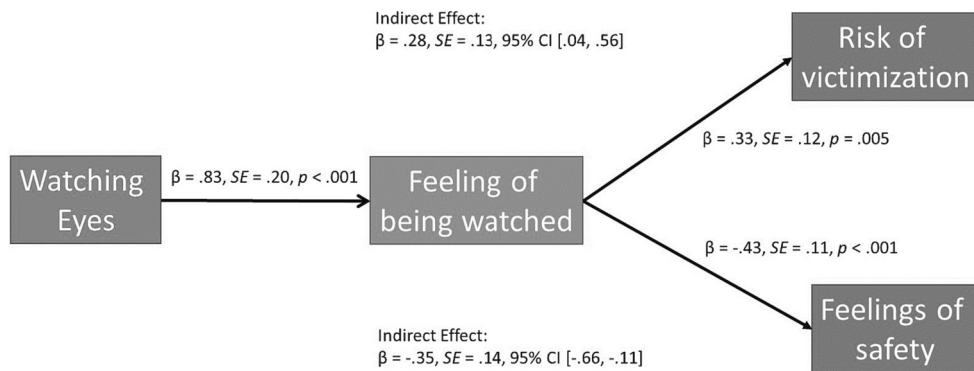
**Trait Fear of Crime.** Trait fear of crime was assessed before participants were exposed to the virtual environments using items from two sources (Pauwels & Pleysier, 2005; Pleysier, 2005). Eight items were used to measure how often participants feel unsafe in certain situations when they occur in real life. Participants could answer on a scale from 1 (Never) - 5 (Always).

As there is no clear measurement of trait fear of crime, the number of items was determined by an exploratory factor analysis. Based on exploratory principal-component factor analysis two factors are extracted. Eigenvalue factor 1 = 3.96, eigenvalue factor 2 = 1.04. Items loading on factor 2 were “In my home I feel safe” and “Does it ever happen that you feel unsafe?”. The latter items cross load on the first factor. With the exclusion of the item “In my home I feel safe” the exploratory factor analysis results in a unidimensional scale. Cronbach’s alpha for the 7 items is 0.86. As such, we use these 7-items for the scale.

**Standard Demographics.** Standard demographics that are regularly associated with both trait and state fear of crime are controlled for in



**Fig. 6.** Notes: Above describes the predicted relationship between the environment, underlying elements, and behavior in our two studies. Directional hypotheses are indicated while exploratory analyses are represented with a dashed line.



**Fig. 7.** Notes. Indirect effects of the watching eyes intervention on perceived risk of victimization and feelings of safety via feelings of being watched.

the preceding analyses. Specifically, we control for gender (female, 80 %) and age ( $M_{age} = 21.1$ ,  $SD_{age} = 3.83$ ).

**Presence, Cybersickness, and Previous Video Game Experience.** Following previous research (e.g., Nee et al., 2019; van Sinte-maartensdijk et al., 2021) we also control for factors that may influence the VR experience, namely, presence, cybersickness, and previous video game experience. Four items on a 1 (Completely disagree) - 7 (Completely agree) scale assessed how present a participant felt in the virtual neighborhoods (Hartmann et al., 2016; van Gelder et al., 2022). Five items scored on a 1 (Completely disagree) - 7 (Completely agree) scale were selected from the simulator sickness scale (Kennedy et al., 1993) to assess core aspects of discomfort (i.e., nausea, stomach ache, dizziness, lack of focus, and blurred vision). To assess VR experience, participants were asked if this was their first time in VR (“yes” = 47.6 %). To assess all other platforms (e.g., game station, cellphone, computer), participants were asked about the frequency of their video gaming. Scores could range between 1 (Never) - 5 (Almost every day).

**4. Results**

**4.1. Study 1 – Motion-activated light and sound intervention**

**4.1.1. Group differences**

Although risk of victimization was descriptively lower, the experimental and control group did not differ significantly ( $M_{exp} = 2.20$ ;  $M_{ctrl} = 2.32$ , Table 1). The same applies to the feelings of safety ( $M_{exp} = 5.09$ ,  $M_{ctrl} = 5.03$ ,  $M_{diff} = 0.05$ , Table 1). We also tested whether feelings of being watched were affected by the light and sound intervention. There was no significant difference between conditions in regards to feelings of being watched (Table 1,  $M_{exp} = 2.36$ ;  $M_{ctrl} = 2.67$ ,  $M_{diff} = -0.31$ ,  $p = 0.272$ ).

**4.1.2. Relational analyses**

There was a strong negative correlation ( $r = -0.77$ ) between perceived risk of victimization and feelings of safety (Appendix B, Table B.1). Trait fear of crime positively correlated with perceived risk

**Table 1**  
Main effects analyses, differences between group means (t-test), Study 1.

	M experimental N = 40	M control N = 44	ΔM	t	p	Cohen’s D
Risk of victimization <sup>a</sup> (H1)	2.20 [1.85, 2.54]	2.32 [1.97, 2.67]	-0.13 [-0.62, 0.37]	-0.508	0.306	-0.11 [-0.54, 0.32]
Feelings of safety <sup>a</sup> (H2)	5.09 [4.63, 5.54]	5.03 [4.60, 5.47]	0.05 [-0.57, 0.67]	0.172	0.432	0.04 [-0.39, 0.47]
Feelings of being watched <sup>b</sup> (exploratory)	2.36 [2.03, 2.69]	2.67 [2.22, 3.13]	-0.31 [-0.86, 0.25]	-1.106	0.272	-0.24 [-0.67, 0.19]

<sup>a</sup> One-sided test, directed hypothesis.

<sup>b</sup> Two-sided test, exploratory analysis, unequal variances across groups, 95 % confidence intervals in brackets.

of victimization ( $r = 0.24$ ), providing support via convergent validity for the measures. In addition, feelings of being watched correlated positively with risk of victimization ( $r = 0.36$ ) and negatively with feelings of safety ( $r = -0.42$ ). Furthermore, participant age negatively correlated with perceived risk of victimization ( $r = -0.28$ ), and gender (female = 1, male = 0) positively correlated with perceived risk of victimization ( $r = 0.24$ ) and feelings of safety ( $r = -0.28$ ). No other significant correlations emerged. Among the control measures there are significant correlations between being female and trait fear of crime, presence, age, as well as gaming experience (Appendix B, Table B.1).

As a final step, we tested our hypotheses in a multiple regression framework. With step-by-step model building, we tested whether results changed with the inclusion of controls. Drawing on OLS regressions,<sup>9</sup> we do not find a significant effect for the motion-activated light and sound intervention on risk of victimization nor feelings of safety (Table 2, Models 1 and 5). The treatment effect does not change when controlling for trait fear of crime (Models 2 and 6), age and gender (Models 3 and 7) and gaming experience, VR experience and cybersickness (Table 2, Models 4 and 8).

In Model 2, trait fear of crime has a significant relationship with perceived risk of victimization ( $\beta = 0.38$ ; 95 % CI: [0.04, 0.72]). However, the effect disappears when controlling for other variables. In the full model (Model 3), age shows a significant negative effect on risk of victimization ( $\beta = -0.0749$ ; 95 % CI: [-0.14, -0.01]). In regard to feelings of safety (Models 5–8) there are no significant results in any of the models. Taking all the results into account, hypotheses 1 and 2 are not supported.

#### 4.1.3. Behavior in virtual reality

To examine behavior in the virtual neighborhood we examined the percentage of walkable area in a neighborhood that a participant traveled. This variable demonstrates how much of the neighborhood a participant explored and gives an estimation of how much the participant was able to perceive the neighborhood as a whole.<sup>10</sup> On average, participants in the control condition explored the neighborhood for 3.83 min ( $SD = 1.34$ ), while participants in the experimental condition explored it for 4.41 min ( $SD = 1.53$ ).

On average, participants in the control condition explored 17.3 % of the walkable area ( $SD = 5.8$ ) while participants in the experimental condition explored 19.9 % ( $SD = 6.9$ ). Another negligible difference can also be observed when comparing the percentage of walkable area in dangerous areas covered (i.e., the water course and alleys; Appendix B, Table B.2,  $M_{exp} = 16.2\%$ ,  $M_{ctrl} = 14.3\%$ ). There is no notable difference between conditions when comparing the percentage of non-dangerous areas covered as well as for the ratio between the number of fields entered in dangerous vs. non-dangerous areas. When entered into the regression models, the percentage of walkable neighborhood traveled does not have a significant effect on any of the dependent variables (Appendix B, Table B.4).

## 4.2. Study 2 – Watching Eyes

### 4.2.1. Group differences

In Study 2, compared to the control condition, participants exposed to the watching eyes signs did not indicate significantly more perceived risk of victimization ( $M_{exp} = 2.43$ ,  $M_{ctrl} = 2.48$ ,  $M_{diff} = -0.05$ ) nor did they indicate significantly less feelings of safety ( $M_{exp} = 4.64$ ,  $M_{ctrl} = 5.01$ ,  $M_{diff} = -0.37$ ; Table 3). Regardless of the intervention, the

perceived risk of victimization is considered low and the participants in both groups feel rather safe. Conversely, participants in the experimental group did indicate significantly more feelings of being watched compared to participants in the control group ( $M_{exp} = 4.05$ ,  $M_{ctrl} = 2.55$ ,  $M_{diff} = 1.50$ ,  $p < 0.001$ ; Table 3).

### 4.2.2. Relational analyses

Similar to Study 1, feelings of safety and perceived risk of victimization were significantly negatively correlated ( $r = -0.74$ ). Like in Study 1, perceived feelings of being watched were significantly negatively related to feelings of safety ( $r = -0.40$ ) and significantly positively related to perceived risk of victimization ( $r = 0.27$ ; Appendix B, Table B.3). In regard to the control variables, unlike in study 1, trait fear of crime was not significantly related to any of the outcome variables (i.e., perceived risk of victimization; feelings of safety; feelings of being watched). In line with Study 1, gender was significantly negatively correlated with feelings of safety ( $r = -0.26$ ). Finally, it should be noted that cybersickness was significantly negatively correlated with perceived risk of victimization ( $r = -0.25$ ) and significantly positively correlated with feelings of being watched ( $r = 0.26$ ).

As a final step, we use multiple regression analysis to examine the influences of condition on the dependent variables while controlling for a variety of factors. In a model which only includes a participant's condition, there is no main effect on perceived risk of victimization nor feelings of safety (Table 4, Model 1 and 5). However, there is a main effect of condition on feelings of being watched (Model 10,  $\beta = 1.517$ ; 95 % CI: [0.80, 2.24]). The inclusion of control variables in all of the models does not change either result (i.e., there is no suppression effect; Table 4, Model 2–4, 6–8, 11–12). Taking the above into consideration, Hypotheses 3 and 4 are not supported. However, Hypothesis 5, that the watching eyes increase feelings of being watched, is supported.

### 4.2.3. Indirect effects analysis

For exploratory purposes we investigated the indirect effects of watching eyes on perceived risk of victimization and feelings of safety via feelings of being watched, using the PROCESS macro for SPSS (Hayes, 2022). Indirect effects analysis is a form of regression-based path-analysis: it provides an estimate of the proportion of variation of a mediating variable (in this case, feelings of being watched) that is explained by a predictor (in this case, the watching eyes condition), which in turn predicts a proportion of variation of the dependent variable (in this case, perceived risk of victimization and feelings of safety). The PROCESS macro for SPSS presents the results of the different regression-based steps for indirect effects analyses (Baron & Kenny, 1986) and additionally calculates the product moment coefficient of the indirect effect. Furthermore, the PROCESS macro estimates the standard error of the indirect effect via bootstrapping, from which confidence intervals can be derived that determine the level of significance of the indirect effect.

The full results of the multi-step regression-based analyses are presented in supplemental materials Table B.5. A visual representation of the indirect effects analysis is presented in Fig. 7. In line with the results above (Table 4), the results of the indirect effects analysis revealed that there was a significant effect of watching eyes on feelings of being watched,  $\beta = 0.83$ ,  $SE = 0.20$ ,  $p < 0.001$ , and also a significant positive effect of feelings of being watched on perceived risk of victimization when controlling for watching eyes condition,  $\beta = 0.33$ ,  $SE = 0.12$ ,  $p = 0.005$ . Importantly, the indirect effect of watching eyes on perceived risk of victimization via feelings of being watched was found to be significant when estimated with 10,000 bootstraps ( $\beta = 0.28$ ,  $SE = 0.13$ , 95 % CI [0.04, 0.56]). Similarly, when testing the indirect effect of watching eyes on feelings of safety, there was a significant effect of watching eyes on feelings of being watched,  $\beta = 0.83$ ,  $SE = 0.20$ ,  $p < 0.001$ , and a significant negative effect of feelings of being watched on feelings of safety when controlling for watching eyes condition,  $\beta = -0.43$ ,  $SE = 0.11$ ,  $p < 0.001$ . Again, the indirect effect of watching eyes on feelings of safety via

<sup>9</sup> All models were estimated with and without robust standard errors and the results do not change.

<sup>10</sup> However, it should be noted that the measure of percentage of walkable area covered is highly correlated with the distance walked (Study 1:  $r = 0.92$ , Study 2:  $r = 0.97$ ) and the time spent in the environment (Study 1:  $r = 0.76$ , Study 2:  $r = 0.71$ ).



**Table 2**  
OLS regression study 1 - motion-activated light and sound intervention.

	Victimization				Safety			
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8
Experimental condition (light & sound)	-0.125 [-0.62, 0.37]	-0.0971 [-0.58, 0.38]	-0.144 [-0.62, 0.33]	-0.144 [-0.62, 0.33]	0.0534 [-0.57, 0.67]	0.0332 [-0.58, 0.65]	0.154 [-0.46, 0.77]	0.175 [-0.45, 0.80]
Trait fear of crime		0.381* [0.04, 0.72]	0.273 [-0.08, 0.63]	0.270 [-0.13, 0.67]		-0.271 [-0.71, 0.17]	-0.0467 [-0.51, 0.42]	-0.0318 [-0.51, 0.44]
Presence			0.151 [-0.05, 0.35]	0.158 [-0.012, 0.33]			-0.0456 [-0.31, 0.22]	-0.0585 [-0.36, 0.21]
Age			-0.0749* [-0.14, -0.01]	-0.0774** [-0.13, -0.02]			0.0420 [-0.04, 0.12]	0.0442 [-0.04, 0.13]
Female			0.164 [-0.53, 0.85]	0.0753 [-0.59, 0.74]			-0.841 [-1.74, 0.06]	-0.851 [-1.90, 0.20]
Gaming experience				-0.0700*** [-0.33, 0.18]				0.0177 [-0.32, 0.36]
First time VR				-0.0654 [-0.53, 0.40]				0.124 [-0.50, 0.75]
Cybersickness				0.109 [-0.15, 0.37]				-0.221 [-0.57, 0.13]
N	84	84	84	84	84	84	84	84
R <sup>2</sup>	0.003	0.061	0.163	0.174	0.000	0.019	0.097	0.118
Adj. R <sup>2</sup>	-0.009	0.038	0.110	0.086	-0.012	-0.005	0.039	0.023

95 % confidence intervals in brackets.

\* p < 0.05.

\*\* p < 0.01.

\*\*\* p < 0.001.

**Table 3**  
Main effects analyses, differences between group means (t-test), study 2.

	M experimental N = 40	M control N = 44	ΔM	t	p	Cohen's D
Risk of victimization <sup>a</sup> (H3)	2.43 [1.99, 2.87]	2.48 [2.10, 2.86]	-0.05 [-0.62, 0.52]	-0.18	0.429	-0.04 [-0.47, 0.39]
Feelings of safety <sup>a</sup> (H4)	4.64 [4.13, 5.14]	5.01 [4.55, 5.48]	-0.37 [-1.05, 0.30]	-1.103	0.864	-0.24 [-0.67, 0.19]
Feelings of being watched(H5)	4.05 [3.50, 4.60]	2.55 [2.06, 3.03]	1.50 [0.79, 2.22]	4.173	0.001	0.91 [0.46, 1.36]

<sup>a</sup> One-sided test, directed hypothesis, 95 % confidence intervals in brackets.

feelings of being watched was significant when estimated with 10,000 bootstraps ( $\beta = -0.35, SE = 0.14, 95\% \text{ CI } [-0.66, -0.11]$ ).

This reveals that, even though there was no support for the predictions that the watching eyes condition would increase perceived risk of victimization and decrease feelings of safety directly, there was a significant indirect effect of watching eyes on perceived risk of victimization and feelings of safety in the expected direction via feelings of being watched.

#### 4.2.4. Behavior in virtual reality

As with Study 1, we examined behavior in the virtual neighborhood by examining how much of the area participants explored. On average, participants in the control condition explored the neighborhood for 4.34 min ( $SD = 1.66$ ) while participants in the experimental condition explored it for 4.65 min ( $SD = 2.09$ ). There are no notable differences between the two conditions in the spatial behavior (Appendix B, Table B.2). Compared to the neighborhood used in Study 1, the design of the neighborhood leads to lower values for the percentage of walkable area covered, but the control group ( $M = 14.3\%$ ) does not meaningfully differ from the experimental group ( $M = 13.9\%$ ). This also applies to the percentage of area covered in dangerous zones and the percentage of non-dangerous areas covered. When entered into the regression models, the percentage of walkable neighborhood traveled does not have a

significant effect on any of the dependent variables (Appendix B, Table B.6) The significant effect of the watching eyes intervention on feelings of being watched in Study 2 is not affected by this additional covariate.

## 5. General discussion

In two studies, we investigated how environmental interventions aimed at reducing crime, may also influence the perceived livability of a neighborhood by examining FOC at the cognitive, emotional, and behavioral levels. In Study 1, we examined the influence of dynamic, motion-activated street lighting and sound on FOC. In Study 2, we took a novel approach towards the watching eyes effect and explored whether it may inadvertently increase FOC.

The results are mixed. We found no support for Hypotheses 1 and 2. Participants in the experimental condition that were exposed to dynamic lighting and sound did not perceive a lower likelihood of victimization nor did they report greater feelings of safety compared to participants in the control condition. In the second study, we found no support for Hypotheses 3 and 4. Participants in the experimental condition that were exposed to a watching eyes sign did not report a higher perceived likelihood of victimization nor did they report decreased feelings of safety. However, we did find support for Hypothesis 5. Participants in

**Table 4**  
OLS regression Study 2 - Watching Eyes.

	Victimization				Safety				Watched			
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9	Model 10	Model 11	Model 12
Experimental condition (watching eyes)	-0.0518 [-0.63, 0.52]	-0.0301 [-0.60, 0.54]	-0.0630 [-0.64, 0.51]	-0.0487 [-0.62, 0.52]	-0.374 [-1.05, 0.30]	-0.392 [-1.07, 0.28]	-0.300 [-0.98, 0.37]	-0.271 [-0.95, 0.40]	1.505*** [0.79, 2.22]	1.517*** [0.80, 2.24]	1.551*** [0.82, 2.28]	1.491*** [0.78, 2.20]
Trait fear of crime		0.326 [-0.08, 0.73]	0.207 [-0.24, 0.65]	0.254 [-0.18, 0.69]		-0.266 [-0.75, 0.22]	-0.0636 [-0.58, 0.45]	-0.0859 [-0.60, 0.43]		0.194 [-0.32, 0.71]	0.165 [-0.39, 0.72]	0.0914 [-0.45, 0.64]
Presence			0.0537 [-0.20, 0.30]	0.0218 [-0.23, 0.27]			0.0693 [-0.22, 0.36]	0.101 [-0.19, 0.40]			0.142 [-0.18, 0.46]	0.186 [-0.12, 0.50]
Age			0.0322 [-0.05, 0.11]	0.0355 [-0.05, 0.12]			-0.0323 [-0.13, 0.06]	-0.0396 [-0.14, 0.057]			0.0740 [-0.03, 0.18]	0.0803 [-0.02, 0.18]
Female			0.525 [-0.33, 1.38]	0.441 [-0.53, 1.41]			-1.069* [-2.06, -0.07]	-1.420* [-2.56, -0.28]			0.0272 [-1.05, 1.10]	0.350 [-0.85, 1.55]
Gaming experience				-0.0214 [-0.34, 0.30]				-0.254 [-0.63, 0.12]				0.171 [-0.22, 0.56]
First time VR				-0.166 [-0.75, 0.42]				0.0681 [-0.62, 0.76]				-0.120 [-0.84, 0.60]
Cybersickness				-0.349* [-0.67, -0.03]				0.288 [-0.09, 0.67]				0.532** [0.13, 0.93]
N	84	84	84	84	84	84	84	84	84	84	84	84
R <sup>2</sup>	0.000	0.031	0.062	0.124	0.015	0.029	0.084	0.129	0.175	0.181	0.211	0.289
Adj. R <sup>2</sup>	-0.012	0.007	0.002	0.030	0.003	0.005	0.026	0.036	0.165	0.161	0.161	0.213

95 % confidence intervals in brackets.

- \*  $p < 0.05$ .
- \*\*  $p < 0.01$ .
- \*\*\*  $p < 0.001$ .

the experimental condition that were exposed to watching eyes signs reported increased feelings of being watched. While this result may seem intuitive, it is not regularly tested in studies that utilize a watching eyes intervention (Pfattheicher & Keller, 2015). Thus, we provide clear, statistical evidence that watching eyes intervention does increase the feeling of being watched as theorized. Researchers and practitioners alike can use this information to tailor and maximize the effectiveness of interventions predicated on the link between watching eyes and the feeling of being watched.

Indeed, additional analyses revealed that watching eyes interventions indirectly increased FOC in regards to cognition and affect, via feelings of being watched. Regarding affect, the watching eyes signs successfully increased negative affect as intended. This is congruent with previous studies indicating that the staring eyes can be perceived as hostile and with that increase negative emotions, such as fear (Manesi et al., 2016; Panagopoulos & van der Linden, 2016). Relatedly, by including the message “burglars we are watching you”, the signs successfully increased the cognitive element of fear of crime.

Since a watching eyes intervention can universally influence anyone who observes it, we suggest that it is possible that such an intervention not only influences motivated offenders, but may also increase negative affect such as anxiety and reputational concerns in law-abiding citizens. Thus, while potentially reducing crime rates, when implementing watching eyes interventions we need to consider how the unintended consequence of increasing FOC may inadvertently reduce overall community wellbeing.

Although no intervention effects emerged in Study 1, it would be erroneous to conclude that lighting does not influence FOC. First, as indicated earlier, the literature varies in how FOC is measured and assessed. Therefore, the discrepancies in findings, including the null results here, may be due to measurement and operationalization differences, and not the lack of an effect (Collins, 2016).

Further, other studies using more traditional methods, such as field studies and in house surveys, show mixed results including null findings (e.g., Ceccato, 2020; Cozens et al., 2003; Green et al., 2015; Pain et al., 2006). Rather than interpreting these methods as invalid, the mixed evidence reveals the complexity of the relationship between lighting and FOC. The discrepancies in results may demonstrate boundary conditions (Ceccato, 2020). For example, studies vary in terms of the location that is assessed, ranging from parking garages, to residential areas, to city streets. The differences in effectiveness could suggest that lighting is more effective in some areas compared to others (e.g., a city alleyway vs. a quiet neighborhood). Indeed, a previous study using 360° videos and virtual reality headsets determined “The effect of installing and improving streetlights on reducing fear of crime is greater in residential areas with low illuminance, particularly when the illumination level is kept at 5 lx or higher” (Son et al., 2023, p. 12).

Most importantly in the context of this study are the diminishing returns on improving street lighting. That is, increasing the light from none to some (e.g., zero to five) is likely to be more impactful than increasing the lighting from some to more lighting (e.g., ten to fifteen). Researchers have described the ideal lighting intervention in regard to luminosity, height of light source, and angle of the light (e.g., Cozens et al., 2003; Kim & Park, 2017). However, there is still heterogeneity in implementation and research. This could equally contribute to the differences in findings. For example, our virtual environments were created using Unity’s High-Definition Render Pipeline, which allows for high-end simulations, including lighting (e.g., behavior of light, shadows, light bouncing, and general luminosity). Additionally, we used *Shadowmask* in ultra-high resolution to create natural and real-time shadows, and all the light posts manipulated in Study 1 were enabled for ultra-high-resolution shadows. However, it is possible that the difference in lighting between conditions was not large enough. When we asked the participants if they had seen the change in lightning, many reported to

not have noticed it. Thus, it is possible that the dynamic lighting was too subtle to have an effect on the participants, resulting in null effects between conditions.

In sum, we do not conclude that there is no effect of lighting on FOC. Instead, our results point to the potential boundary conditions under which lighting might be most impactful. Specifically, the impact of lighting may be most effective as a binary change (e.g., going from no lighting to bright lighting) rather than gradual. We hope readers view this result as another data point in the growing literature that seeks to better understand under what conditions improved lighting affects FOC.

Secondly, sound, especially music, has a soothing effect and increases feelings of safety (Aletta et al., 2016; Eastal et al., 2014; Lavia et al., 2016). In Study 1, the majority of the sounds explicitly included, or indicated the presence of others (e.g., people talking, the sound of a dinner party, a TV being on). As indicated in the literature review, we chose these sounds to create the illusion of other people being around and increase the feelings of safety. However, it is possible that other sounds (e.g., music) may have had a greater effect. Examining what sounds in what environments decrease fear of crime would be an interesting avenue for future researchers.

### 5.1. Limitations

The different interventions used in these studies contribute to the overall knowledge in FOC, safety, and the general development of VR research. However, the results should be viewed in light of some limitations. First, our sample was largely student based and succumbs to the limitation of being WEIRD<sup>11</sup> (Henrich et al., 2010). While this is still commonplace in the social sciences, it is possible the results here would not replicate in a non-WEIRD sample. Additionally, the null-effects of this study could be due to methodological issues. First, it could be that our sample size was not large enough to generate an effect. The sample was drawn from convenience during the middle of the COVID-19 pandemic. As such, it is possible that we are not operating with enough power.

FOC is a complex construct influenced by multiple situational and dispositional factors. To be testable, we had to narrow our focus, definition, and measurement of FOC. In this way, we may have reduced our ability to replicate the findings from real-world observations. Recall that the affective element of FOC includes feelings of safety and visceral fear. Although we analyzed feelings of safety, the interventions may have only reduced visceral fear but not actually increased safety. That is to say, feelings of safety may not be the exact opposite of feelings of fear, and an intervention may not influence both of them (e.g., Rodin, 1978).

Finally, although we believe our behavioral variable of percentage of the walkable area covered serves as a better measure compared to the traditional distance traveled and time spent in the environment, it is not without flaws. There is a key distinction between walking in an area and being able to observe that area. For example, one may be able to stand in one corner of a room and observe the whole room without having to traverse every square foot of it. Therefore, it is possible that participants did not need to physically walk down a (non-)dangerous area in order to feel like they explored or observed it. This means participants may not have walked in an area not because they were avoiding it, but simply because they were uninterested in exploring that area because they could see what was there without having to walk through it.

### 5.2. Future research

Future researchers interested in crime reducing interventions could consider narrowing the scope of their investigation and focus on only one intervention (e.g., light). For example, to better understand under what conditions light is effective in reducing FOC, researchers could

investigate degrees of lighting, including binary conditions (e.g., no light versus bright light). This would allow for testing incremental effects. Researchers could also examine the role of lighting in different locations by drawing on the literature of Fisher and Nasar (1992) and Goffman (1971), comparing the effectiveness of lighting interventions in areas that vary in their degree of refuge, prospect, and escape. For example, a poorly lit pedestrian tunnel, public park, and public parking area all differ in their degree of refuge, prospect, and escape. However, it remains an empirical question if improved lighting is equally effective at reducing FOC across all three locations. By taking this approach, researchers will not only be able to tease apart when lighting is most effective, but provide key practical guidance to practitioners on where interventions should be placed, maximizing resources. Although we considered such approaches, we chose to focus on different interventions in residential areas. This allowed us to be able to test for interaction effects, and to be able to identify differences in the strength of effects.

Similarly, researchers may wish to investigate how different sounds influence the level of FOC. For example, by distinguishing between different sound conditions (i.e., human sounds or music) researchers may test and set the boundary conditions in regard to sound decreasing fear of crime. Researchers may also examine different versions of watching eyes signs to assess which types generate stronger effects. More generally, it may also be observed that in certain contexts outside of fear of crime, watching eyes may bring more comfort or pleasure, such as when giving a performance.

## 6. Conclusion

In two studies we sought to examine how environmental features influence the cognitive, affective, and behavioral elements of Fear of Crime. Although we only find mixed support for our hypotheses, it would be an error to conclude the environment, particularly lighting, does not influence Fear of Crime. Instead, the results of Study 1 suggest that lighting may be most effective when the differences are stark and/or in specific locations (e.g., a commercial city street versus a quiet residential street). Additionally, the watching eyes intervention used in Study 2 indirectly increased perceived risk of victimization and reduced feelings of safety via feelings of being watched. This holds important implications when implementing watching eyes interventions, suggesting we need to consider the potential for unintended negative consequences. In conjunction, the results of both studies suggest that environmental interventions are neither simple nor universal, and can have unintended consequences. As such, researchers and practitioners alike need to test the boundaries of such interventions to better understand what interventions will work best, in which environment, and with the least amount of cost.

### Funding

Not applicable.

### Pre-registration link

[https://osf.io/hp6wd?view\\_only=90dbe398d1184ddd6b6254e683fee9dc](https://osf.io/hp6wd?view_only=90dbe398d1184ddd6b6254e683fee9dc).

### CRedit authorship contribution statement

**William P. McClanahan:** Writing – original draft, Writing – review & editing. **Carmen S. Sergiou:** Writing – original draft. **Aniek M. Siezena:** Investigation, Writing – review & editing. **Dominik Gerstner:** Formal analysis. **Henk Elffers:** Resources, Writing – review & editing. **Job van der Schalk:** Conceptualization, Methodology, Project administration, Supervision, Writing – review & editing. **Jean-Louis van Gelder:** Conceptualization, Funding acquisition, Methodology, Project

<sup>11</sup> Western, Educated, Industrialized, Rich and from a Democratic society.

administration, Supervision, Writing – review & editing.

## Declaration of competing interest

None.

## Data availability

The dataset was made available through private access for the purposes of the study. Data will be shared with other researchers for scientific purposes only (e.g., verification, secondary data-analysis, meta-analyses etc.). Upon publication, data will be made available in line with FAIR guidelines.

## Acknowledgements

We thank Charelle Beckman Lapré for their assistance in data collection. We also think Marco Otten for building the virtual environment.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cities.2024.104823>.

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