

# VIRTUAL REALITY AS A NEW TOOL FOR TRANSPORT DATA COLLECTION

Laura AGUDELO-VÉLEZ<sup>1</sup>, Iván SARMIENTO-ORDOSGOITIA<sup>2</sup>, Jorge CÓRDOBA-MAQUILÓN<sup>3</sup>

<sup>1, 2, 3</sup> Department of Civil Engineering, Universidad Nacional de Colombia, Sede Medellín, Colombia

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## Abstract:

Transport studies that adopt complex analyses present methodological challenges that lead to the use of innovative techniques to address the limitations of traditional methods. In the Latin American context, people consider security as a relevant variable in their daily lives. Thus, when people travel around the city and choose a mode of transport, security becomes an important factor and should therefore be included in transport studies. However, the definition of security in terms of transport in the Colombian context remains unclear. Therefore, we examined the security perception effect on transport mode choice by addressing security as a latent variable consisting of three elements: environment, subject and transport mode. We proposed the use of virtual reality (VR) to recreate travel routes and offer participants a scenario of choice closer to the natural conditions of a trip. The participants were provided routes in the form of immersive 3D videos recreating natural trip conditions to identify their choices and travel behaviour. Recordings were made of daily scenarios and existing urban environments portraying real and active modes of transport, giving respondents an almost-natural experience. The use of 360-degree immersive videos offers a multisensory experience allowing both the capture of socioeconomic and travel information and the collection of journey perception. The experiment evaluated two environments in Medellín, Colombia (secure (E1) and insecure (E2)) and studied the effects of lighting conditions (day (D) and night (N)). A total of four videos (E1D, E1N, E2D and E2N) depicting six transport modes in tandem were assessed by 92 participants from Medellín and Bogotá, Colombia. We found that environment-associated security perception varies depending on the time of the journey (day/night) and one's familiarity with the environment. The research results position VR as a tool that offers high potential to support transport studies. We found that people's movements, gestures and expressions while participating in the VR experiments resembled what was expected from journeys in reality. VR constitutes a relevant tool for transport studies, as it allows for an assessment of active transport mode perceptions. It prevents participants from being exposed to the risk associated with travel to specific places and carries out several routes in different transport modes even when participants cannot or have never undertaken journeys in the modes under assessment.

**Keywords:** virtual reality, user's behaviour, transport choice of mode, environment and security

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## Contact:

1) [liagudel@unal.edu.co](mailto:liagudel@unal.edu.co) [<https://orcid.org/0000-0002-1940-7826>] - corresponding author, 2) [irsarmie@unal.edu.co](mailto:irsarmie@unal.edu.co) [<https://orcid.org/0000-0001-7287-4573>], 3) [jecordob@unal.edu.co](mailto:jecordob@unal.edu.co) [<https://orcid.org/0000-0003-4057-1134>]

## 1. Introduction

Traditional tools for gathering journey-related information and transportation modelling have been limited to surveys. These have been framed as static situations and assess typical trips appealing to past experiences (revealed preferences, RP), hypothetical situations (stated preferences, SP) or automatic associations between objects and their positive constructs (automatic preferences, AP). AP surveys, which have relied on the subconscious link between an object and its positive constructs, generate pro-behaviour choice (Córdoba, 2014). The subconscious choice-making process at the subconscious level makes participants less vulnerable to manipulation through presented information in the RP or SP surveys. We propose the use of virtual reality (VR) as a safe and flexible instrument to capture reliable primary data on transport mode decision-making.

VR is a versatile and flexible technique for trip data collection in reliable, close-to-natural conditions. VR allows for a recreation of urban route conditions and trip experiences, overcoming the limitations of SP or RP surveys (Bogacz et al., 2020) and increasing the realism of SP experiments. The use of VR in transport studies might improve decision-making comprehension and public policymaking regarding sustainable mobility. VR has high potential to support transport research and phenomena associated with the subject-territory relation.

Understanding transport mode choice behaviour is more complex in developing countries than in developed ones (Alex et al., 2019). Hence, we examined the security perception effect on transport mode choice. We considered security as a latent variable with three elements: environment, subject and transport mode. The use of VR enables the assessment of multiple combinations of environmental situations, subjects' conditions and transport modes and the evaluation of their independent impacts. The proposed technique removes participants' exposure to physical risk, one of the most important ethical considerations in this type of research. Experiments conducted using VR would allow the researcher to capture additional information in the form of participants' behaviours, expressions and reactions. This would then provide additional tools for urban and transport planning.

Because security perceptions are subjective, we included subjects' characteristics and avoided treating people as homogeneous rational-utility-maximiser

beings with complete information. We used *subject* to emphasise our consideration of individual characteristics such as personality traits, habits, behaviours, thoughts, beliefs, perceptions, emotions and executive function as determinants of their security perception and thus transport mode choice. This was in contrast to the broadly used *user*, which refers to anyone who uses a transport mode. We also included variables such as time, cost and the subject's socio-economic characteristics, which are widely documented in the literature as determinants of transport mode choice. We found differences in security perceptions depending on the environment in which the trips were made. This highlights the relevance of the environment in one's choice of transport mode. We found that mode affects transport mode choice as well; according to our data, cars are perceived as the most secure mode, independent of the journey's environmental conditions and the subject's characteristics. Besides this introduction, this paper is organised into six sections: a background that guides the study's methodological development, followed by the methodology and the collection of primary information. It then presents the results, discussion and concludes the study.

## 2. Background

Wann and Mon-Williams (1996) defined VR as three-dimensional interactive environments generated via computers. In this work, we created real scenarios through 360-degree immersive videos recorded from urban environments. This allows for more credible conditions associated with people's movement in different transport modes through various urban environments and elicits a multisensory experience to evaluate their perceptions. According to Rovira et al. (2009) and Slater et al. (2006), VR adds realism to experiments despite individuals' awareness of the artificial nature of the scenarios and is a powerful tool for investigating human behaviour (Brookes et al., 2020). Animesh et al. (2011), Faiola et al. (2013), Jennett et al. (2008) and Nah et al. (2011) found that VR allows users to be immersed in an established environment and thoroughly assess their perceptions of such an environment. It is also enables user behaviour analysis. Sobhani et al. (2017), who studied multitasking using VR, such as walking and smartphone usage, found the tool useful for a close simulation of pedestrian behaviour in real conditions. O'Neill (1992), Ruddle et al. (1997) and

Tlauka and Wilson (1996) concluded that people can develop realistic spatial knowledge in VR.

In transport studies, Farooq et al. (2018), Moussa et al. (2012), Frankenhuys et al. (2010), Underwood et al. (2011), Erath et al. (2017) and Patterson et al. (2017) used VR and provided evidence of real participant behaviour associated with traffic. Farooq et al. (2018) stated that an important advantage of VR-based research is the ability to examine multiple scenarios and assess treatments or policies and their effects before making decisions.

The VR used in this research offers a better approach than the one that could be obtained one from an exercise supported by SP surveys, as it allows for the analysis of scenarios with greater realism through route-setting involving sound and actual environmental conditions. According to Wang et al. (2016), an immersive VR environment consists of a head-mounted display device that uses an optical system to present scenes through a screen and works with the human brain to produce a strong immersive sensation. One of its limitations, however, involves the use of computerised environments with lags or low-resolution graphics (Loomis et al., 1999), which were eliminated by recording images of a real environment. VR immersion allows participants to move and interact with the environment as if they were in a real journey. Swivel chairs were employed to allow participants to move. VR is an emerging interactive technology that enables transport studies to incrementally implement certain applications on human perception and behaviour.

Mujber et al. (2004) addressed the applications of VR in manufacturing processes and stated that VR has been successfully implemented in several other areas such as rapid prototyping, scientific visualisation, engineering and education. Likewise, Górski (2017) demonstrated how VR is used in engineering with a knowledge-based approach.

Meanwhile, Mantovanni et al. (2003) used VR training for healthcare professionals and said, 'Virtual Reality represents a promising area with high potential of enhancing the training of health-care professionals. Virtual Reality Training can provide a rich, interactive, engaging educational context, thus supporting experiential learning-by-doing'. Likewise, Aziz (2018) observed that VR applications in healthcare demonstrate the potential to address cognitive, psychological, motor and functional impairments and also provide opportunities for training

clinical practitioners. Similarly, Boucharde et al. (2017) used VR to examine social anxiety disorder. In the field of social work, Lanzieri et al. (2021) showed that virtual simulation is a learning/teaching strategy that aims to enhance the connection between classroom learning and professional applications. Scholars have confirmed that students feel more comfortable and less under pressure to perform in virtual settings than in traditional face-to-face role play (Fitch et al., 2016).

### 3. Methodology

Agudelo (2019) suggested that an individual's transport mode choice depends on their security perception as well as traditional variables such as time, cost and socioeconomic characteristics. She considered security as a latent variable formed by three elements: environment, subject and mode. The experiment design involved finding a technique that combines three security perception elements and six transport modes while acknowledging travellers as subjects. The number of combinations among these factors would be unsuitable for treatment through SP and RP. This complexity of the exercise led to a search for alternative tools to recreate different scenarios and combinations that were generated.

We proposed assessing the environment element of security perception as a dual factor that involves immersing participants in recorded videos in positive-secure and negative-insecure environments. Considering Agudelo's (2019) perception of security in social cartography and focus-group findings along with findings by Perone and Tucker (2003), Delbosch and Currie (2012), Iglesias et al. (2013), Sillano et al. (2006) and Puello and Geurs (2015), we evaluated two environments –daytime and night-time. The experiment considered the six transport modes available in Medellín (walking, cycling, metro/bus rapid transit (BRT), bus, motorcycle and car). We isolated the effect of the three elements of subjective security perception by exposing different subjects to the same scenarios.

The use of VR in transport research shields participants from risks associated with travel to specific places (two in this case) and carries out several routes in different transport modes (six). This technique reduces difficulties arising from participants being required to conduct the multiple combination trips for this experiment. Limitations in traditional research techniques include the need for participants

to have driving licences and to have knowledge, skills and aptitudes for driving individual transport modes, such as motorcycles, bicycles and cars. In addition, to standardise the experiment, it was necessary to maintain the same distances by mode, the same time of day or night and the same environmental conditions, among others. This would not be possible unless all people could travel at the same time, which is practically unfeasible.

These difficulties became great challenges to research and triggered a search for new techniques that would allow for the collection of quality information from different combinations that must be evaluated. This led to the use of VR, through which the required assessments could be made, as this technique makes it possible to record a real scenario and have it evaluated by all participants, guaranteeing a standardised experiment in terms of the scenarios for assessment.

To develop this methodology, three steps were carried out: definition and construction of scenarios, context of choice and sample conformation.

### 3.1. Definition and construction of scenarios

We selected two sectors of the city of Medellín, one with conditions of security and the other insecurity. This selection considered the characteristics associated with security/insecurity according to the literature and Agudelo's (2019) findings. Agudelo (2019) collected data from a 12-participant focus group and a 432-participant social cartography developed at different periods in 2016. The description of the travel experience of different subjects and the ethnographic work allowed the selection of elements to be included in the film record. In addition, the activities, actions, behaviours and attitudes of travellers and nontravellers were established in the recording.

We evaluated environments that the population classified as secure (E1) and insecure (E2). Lighting, reported in the literature as a determinant of security perception and one of the most recurrent categories in Agudelo's (2019) focus group and social cartography, was directly associated with the variation between daytime (D) and night-time (N) (illuminated or nonilluminated, respectively). The video production considered other elements associated with the security/insecurity of transport modes, such as the presence of the homeless, activity of street vendors, nontransparent enclosures, busy places (active), solitary places, driving conditions, public transport

stops, building conditions, lane segregation by user type (vehicle, bicycle, sidewalk) and behaviours of different actors on the street.

Figure 1 shows images of the evaluated environments (secure (active place) and insecure (lonely place)).



Fig. 1. Sample images with secure (up) and insecure elements (down). Source: Agudelo (2019).

For each environment (secure and insecure, day and night) we recorded footage with a duration of approximately eight hours. We used a Xiaomi Mi Sphere camera (23.88 MP, video 3.5K) mounted on the head of a person who made real trips in the six transport modes. The tours were recorded as the person travelled, which served as the input for the construction of the 360-degree videos. The final videos for the experiment were produced through a process of scene selection and editing. Four video scenarios that were 10 to 15 minutes long were constructed: secure day environment (E1D), insecure day environment (E2D), secure night environment (E1N) and insecure night environment (E2N). All these scenarios with the six defined transport modes were evaluated by the participants.

To recreate conditions as close as possible to the natural environment, we registered real places in the

city (Figure 2, right). Meanwhile, the computer-recreated scenarios (Figure 2, left) did not offer natural experiential possibilities and could constraint the assessment of subjective security perceptions; hence, this option was rejected. The selected option was the recording of real places in the city, including recorded sounds that enlivened the exercise and provided a more natural and immersive condition. For the participants' experience, we used 3D glasses with hearing aids (Veer OASIS VR headphones) and a smartphone. The video display was made using the Android app 'VaR's VR player PRO'.



Fig. 2. Computer-simulated 3D image (up) and real 3D image and 360-degree recording for this research (down). Source: Agudelo (2019)

### 3.2. Context of choice

We conducted a blind experiment, in which one of the primary outcomes to be evaluated was the perception of security. The participants were unaware of the secure or insecure status of the proposed scenarios. As previously mentioned, the main researcher established the definition of secure and insecure according to the literature review, focus groups and social cartography; however, such information was not provided to the participants.

In a recreated VR travel situation, the subject travelled through the study scenarios (E1D, E1N, E2D and E2N). Each scenario is the combination of one

environment with one period (day or night). Every participant virtually used each transport mode (walking, cycling, metro/BRT, bus, motorcycle and car) in the scenarios so that they can describe and qualify their perceptions of security when travelling. Information were gathered as follows:

1. A socioeconomic and travel characterisation survey was conducted.
2. The secure day environment video was observed (E1D).
3. The respondents rated their security perception in each mode using a seven-point Likert scale.
4. Among the different transport modes used in the virtual route, the respondents chose the one that provided the highest perception of security without considering time and cost. While it is true that time and cost are significant for one's choice of transport mode, they were excluded from this exercise, as they have been extensively studied and reported in the literature. According to Juhász et al. (2017), travel time is a fundamental factor in transport modelling. The selection was made in accordance with the following instruction: *Consider that you should make a route like the one presented in the video. If you have to make a trip on the same route you have just travelled and you have available the six transport modes of presented (walking, cycling, metro/BRT, bus, motorcycle and car) – that is, you can choose the one you want, no restrictions of any kind. According to the perception of security, which of the modes would you choose to travel on the route you have just completed? Please note that your choice refers to this specific route, not associated with the routes you usually take. Mark with an X the image of the chosen mode.* This instruction included a reminder for participants to exclude time and cost as elements of their choice.

These four steps were repeated for the insecure day environment (E2D).

5. After observing the two-day videos (E1D and E2D), the respondents were asked to choose one of the two environments and were given the following instruction: *Consider that you must make a route equal to those presented to you in the video. Which of these two environments do you choose, considering the perception of security? Consider that your choice refers to these journeys in specific, is not associated with the*

trips you usually make. Mark the box below the photo with an X.

The same process was applied to the assessment of the night environments (E1N and E2N). At the end of each video (E1D, E2D, E1N and E2N), the participants evaluated their perception of security by mode in each scenario and chose their preferred mode for that route in terms of security. In addition, after completing each module, the respondents described the reasons that motivated them to assign each qualification as well as indicated the elements, actions or situations that they associated with security/insecurity. The analysis of these narratives is beyond this study’s scope. The participants rated their perception of security by mode for each of the four scenarios. The survey used generic schematic images that did not contain logos or colours associated with real modes to avoid bias (Figure 3).

**3.3. Sample conformation**

The participants were selected through convenience sampling. Based on the data of the Medellín Origin Destination Survey ODS-2012 (AMVA-2012), the user profiles of the study area in terms of socioeconomic characteristics (gender, age, strata and employment status) were defined. ‘The strata system (estratos) is a geographical classification that identifies areas according to the external characteristics of the neighbourhood and dwellings where people live’ (OECD, 2016). Areas are classified into six strata, with strata 1 being the lowest, corresponding to those of lesser quality and strata 6 being the highest, corresponding to the best conditions. From these profiles, this study selected participants who wanted to voluntarily participate in the research and who met the associated characteristics, mainly age, gender and employment status.

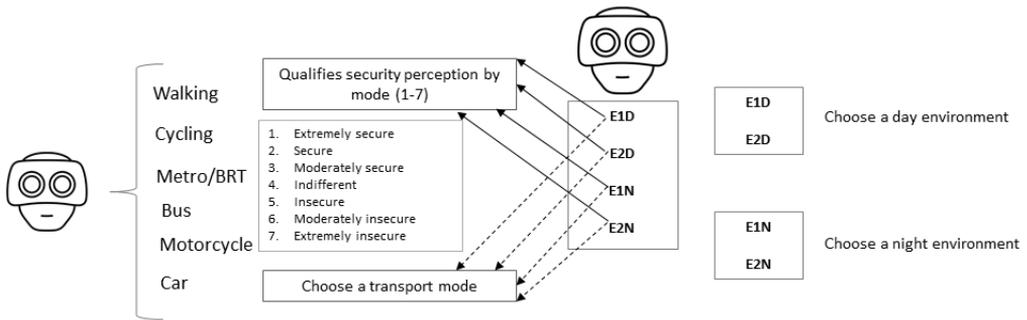


Fig. 3. Methodological process for the execution of the experiment

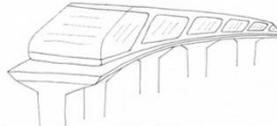
ENVIRONMENT 1 DAY		
Walking	Cycling	Metro
		
Bus	Motorcycle	Car
		

Fig. 4. Transport modes presented to participants

Ninety-two participants underwent the experiment, and the results were reported afterwards. Familiarity with the environment is vital to the perception of security (Agudelo, 2019). We controlled for this effect by exposing people from two different cities to the same environment. Considering that the videos were recorded in Medellín, Colombia, data collection was divided into two subsamples: 77 from Medellín and 25 from Bogotá. Figure 4 presents the execution of the VR experiments.



Fig. 5. Preparation of the participants and execution of the VR exercise. Source: Agudelo (2019)

#### 4. Results

Considering that the discussion in this paper is part of a broader investigation, five results mainly associated with the VR experiment were presented. These are (1) method robustness, (2) ratings of security perceptions of transport modes in different environments, (3) choice of environment based on security, (4) choice of transport mode based on familiarity with the surroundings and (5) choice of environment based on familiarity with the surroundings.

Around 42% of the participants were women. Approximately 95% of the respondents reported work

and study as their reasons for travelling, and the most used transport modes were metro and bus (24% and 23%, respectively). In terms of age group, majority of the participants were from the 20–39 age bracket (67%). The income level for 48% of respondents ranged from USD100 to USD400 (300,000–1,200,000 COP in 2019; COP is the Colombian currency, and this range is less than the minimum).

##### 4.1. Method robustness

The use of VR in this experiment enabled us to observe the participants' involvement in the recorded journeys. We found that their movements, gestures and expressions were consistent with what was expected for the screening conditions. VR is a relevant tool for transport studies, as it allows for the evaluation of active transport mode perceptions. These conditions cannot be achieved through RP or SP experiments where choices are immediately made after undertaking the experimental journeys—just at the moment when the sensations are ongoing. The observations of participant behaviour feed the analysis and public policy design.

##### 4.2. Mode security perception in different environments assessed via VR

We compared the security ratings for each mode among the four environments. We analysed whether the modes received the same ratings in different environments (secure and insecure) during daytime and night-time. Considering that the sample data does not follow a normal distribution, this study used the nonparametric Kruskal–Wallis test to account for differences in the ratings for the same mode in various scenarios.

For the bus and car modes, no differences were observed in security perception for the different scenarios ( $P = 0.096$  and  $0.821$ , respectively;  $>0.05$ ). In the case of cars, the ratings were not statistically different between day and night because they were always within the security range in all scenarios based on the Likert scale (Figure 2). In the case of buses, a similar situation to that of cars was observed; the scores were always in the same range in all the evaluated scenarios. In the other four modes, there were differences in perceptions of security depending on the scenario. In these cases, the ratings depended on the environment (secure/insecure) and time (day/night).

Variations in mode scores, depending on the scenario, indicated that people differently perceive mode security in that environment and at that time. This means that the environment is important to one's security perception associated with mode of transport.

Close to 61% of respondents rated walking in a secure day environment (E1D) in the security range (between moderately secure to extremely secure), while 30% placed this scenario in the insecure range (moderately insecure to extremely insecure); the rest were indifferent. Meanwhile, riding the bus was similar to walking, as 64% placed it in the secure range, while 23% considered it in the insecure range. Figure 6 presents the security perceptions of the different modes in the two environments both day and night. The vertical axis shows the seven levels of security perception ratings from extremely secure (1) to extremely insecure (7). The distribution of the bars corroborates what was obtained from the Kruskal–Wallis test.

Figure 6 illustrates the weight and relevance of transport mode in one's perception of security, and as previously mentioned, cars always receive ratings in the secure range regardless of whether people travel in secure or insecure places; that is, they travel by car, they feel secure.

The metro and BRT also received ratings in the secure range, but there was greater variability in the

insecure day environment (E2D). Meanwhile, ratings for walking varied between the two scenarios; it is considered safe in the secure environment both during the day and at night, while it tends to be perceived as unsafe in the insecure environment and much more so at night. For buses, the perceptions remained constant towards the centre of the rating scale since, in general, the bus is not perceived as insecure. This is a positive result for the study overall and for the definition of sustainable mobility policies. Stakeholders may take advantage of the security perception ratings for buses to gain more users and thus move society towards sustainable mobility practices.

Meanwhile, to compare different environments and thus determine changes in the security perceptions of each mode depending on the travel environment, post-hoc tests were conducted. To analyse the results, this study conducted a Bonferroni adjustment, through which an  $\alpha$  adjusted value (0.0083) was obtained according to the six comparisons between the four scenarios defined for the analysis of the environments. For this comparison, the car and motorcycle modes were not included since according to the Kruskal–Wallis test these modes showed no differences in security perception among different scenarios.

Table 1. Descriptive statistics of the participants

Variable	Characteristics	Sample (%)	ODS (2012) (%)
<b>Gender</b>	Male	58	56
	Female	42	44
<b>Age</b>	20 or less	7	9
	20–24	30	30
	25–29	15	16
	30–39	22	23
	40–49	13	12
	50–59	9	8
	60 or above	4	3
<b>Reason for travel</b>	Work	52	54
	Study	42	43
	Other	6	4
<b>Employment status</b>	Employed	38	40
	Student	34	33
	Employed and student	23	20
	Housewife	2	3
	Other	3	4

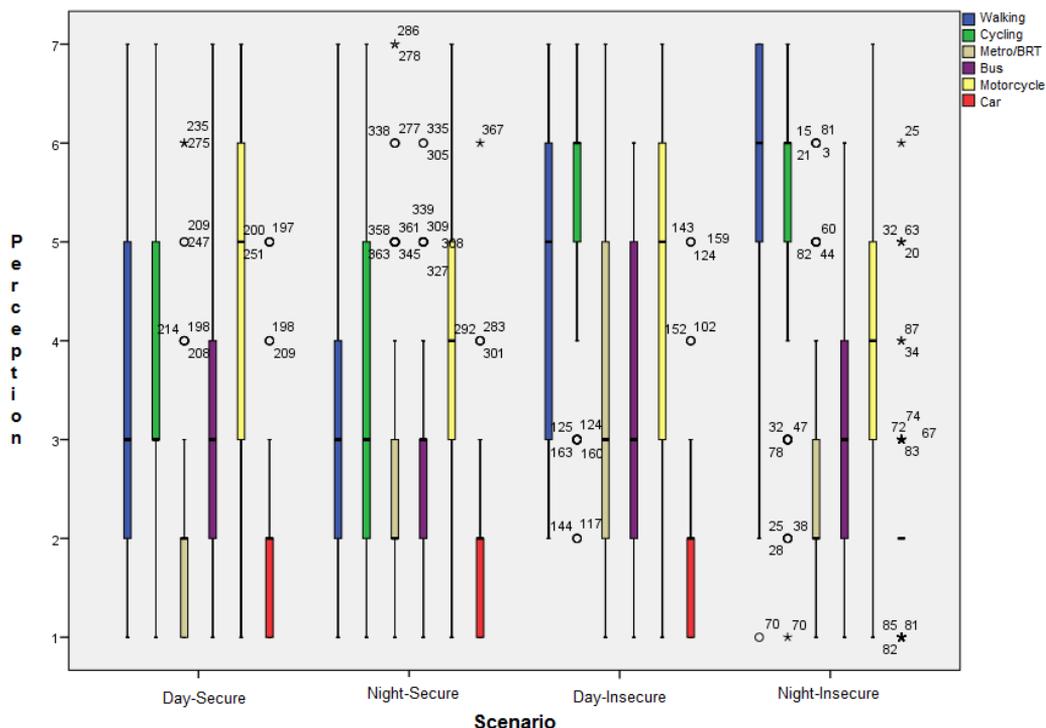


Fig. 6. Mode security perception in both environments combined, day and night

The results showed that when people choose transport modes based on security to travel the VR proposed routes, they were inclined to use cars, which were not part of the modes that aim for sustainable mobility. This finding is consistent with López et al.'s (2014) assertion that habits created around transport modes used for daily commuting can hinder sustainable mobility, as they prevent people from changing decisions despite having alternatives.

Regarding the choice of mode according to gender and age, this study found that in a secure day environment, more women chose the metro than men. In this scenario (E1D), an association was observed between the selected mode and gender (likelihood ratio = 0.013 < 0.05) whereas age did not influence the choice of mode in any scenario. Younger people usually chose walking and cycling, while senior participants chose metro and BRT. In an insecure night environment, no participant chose walking and cycling.

In addition, to compare scenarios and check for differences in each mode, multiple Mann–Whitney U tests were performed, adjusting the P-value by the number of scenario combinations.

**a) Day secure (E1D) –night secure (E1N)**

In the secure environment, there were no differences between day and night for walking, cycling and motorcycle, as their significance values were higher than the  $\alpha_{adjusted}$  adjusted value (0.0083); this is because the medians and percentiles (25 and 75, respectively) were almost equal. Differences were observed only in the perception of security in the metro/BRT mode ( $p = 0.000, < 0.008$ ). This may be associated with the volume of people, as there were fewer people during the day than at night in the VR experiment. The respondents said that their perception of security decreases when the mode gets crowded—a situation that did not occur during the day virtual route with fewer people. Meanwhile, with respect to cycling, differences were found in the medians, but these were not significant ( $P = 0.017, > 0.008$ ).

**b) Day secure (E1D)–day insecure (E2D)**

In this relation, differences were observed between walking, cycling and metro/BRT ( $p = 0.000, < 0.0083$ ) whereas for the motorcycle mode, no differences were found in the perception of security between secure and insecure environments during the day.

**c) Day secure (E1D)–night insecure (E2N)**

As in the previous case, differences were found between walking, cycling and metro/BRT. The motorcycle mode showed no differences in perceptions between these two scenarios.

**d) Night secure (E1N)–day insecure (E2D)**

Again, there were differences in all modes except motorcycle.

**e) Night secure (E1N)–night insecure (E2N)**

In this case, differences were observed in security perceptions between the walking and cycling modes whereas no differences were found in security perceptions between the BRT and motorcycle modes.

**f) Day insecure (E2D) –night insecure (E2N)**

For this relation, there were differences between walking, cycling and metro/BRT whereas there were no differences in perceptions for cycling and motorcycle.

Table 1 summarises all the differences in the security perceptions of the modes between the different environments.

Walking, cycling and metro/BRT generally showed differences among different scenarios whereas bus and car only presented differences between day insecure and night secure scenarios.

**4.3. Choice of environment based on security**

As expected, most of the respondents (92%) chose the secure environment (E1) both in the daytime and night-time. Note that this was a place with a secure connotation (but this information was not provided to the respondents).

**4.4. Choice of mode based on familiarity with the environment**

The previous section referred to all analyses as one aggregate sample. Here and in the next section, to analyse the familiarity effect, the sample was divided into two subsamples, one from Medellín and the other from Bogotá. There is an association between familiarity and mode choice in the insecure day environment (E2D,  $p = 0.049$ ). In this scenario, cars were the most preferred mode, chosen by 73%

of participants who were familiar with the environment (surveyed in Medellín). In addition, 54% of those who were unfamiliar with the environment (respondents from Bogotá) also chose the car mode. The second preferred mode according to the perception of security and its relation to environment familiarity was the BRT: 18% of those who chose it were familiar with the environment, while 12% were not. These results clarify the reasons why people from Bogotá would use cars less frequently in Medellín. People with less familiarity seem to perceive lower risk, or they do not want to drive in an environment that is not familiar to them. This factor of familiarity must be investigated more.

**4.5. Choice of environment based on familiarity with it**

In all cases, the participants' most preferred environment was E1 regardless of their familiarity with it. According to the chi-square statistical test, no association exists between choice of environment and familiarity.

Table 2. Modes with differences in perceptions among different scenarios

	Day insecure	Night secure	Night insecure
Day secure	Walking, cycling, metro/BRT	Metro/BRT	Walking, cycling, metro/BRT
Day insecure		Walking, cycling, metro/BRT, bus, car	Walking, cycling, metro/BRT
Night insecure		Walking, cycling.	

**5. Discussion**

Our study recorded real scenarios of urban environments and was not limited to computer-created animations or images like those traditionally used in driving simulators and VR exercises in both transport and other areas of knowledge such as health (Mantovanni et al., 2004; Aziz, 2018; Bouchard, 2017), manufacturing (Mujber et al., 2004), engineering (Górski, 2017) and social work (Lanzieri et al., 2021). In our study, consistent with Loomis's (1999) findings, the problem of lagged images was addressed by recording videos of real scenes that provide a greater degree of realism to the experiment and enable respondents to interact with the evaluated scenario.

Schwebel et al. (2008) tested the validity of virtual environments in a study that evaluated the behaviour of pedestrians in immersive environments as well as in real conditions, finding significantly correlated behaviour in both real and virtual scenarios between child and adult pedestrians.

Deb et al. (2017) also showed the validity of pedestrian simulators. Their study did not include ambient sounds (wind, environment, conversations, etc.) and only considered the sounds of cars, which was why participants gave the noise had a low rating compared to other characteristics, which showed the simulator's acceptability and utility. The VR videos used in our research included the sound of the environment, that is, vehicles, people, music and all the sounds in a moving city. This helps increase the degree of realism of the evaluated scenes.

The limitations inherent in transport studies were mainly derived from SP and RP surveys, based on which approximations were obtained for conditions of choice of transport mode and how a respondent perceives behaviour in the face of a hypothetical situation. This study addressed these limitations by recording real city scenes, in which the participants were immersed through VR devices. The interactions displayed the respondents' behaviour and expressions throughout the experiment.

None of the traditional techniques in transport studies have predicted with certainty the choices of users, neither was it possible to exactly represent participants' decisions. However, the specificity of the VR exercise used in this research helped diminish some limitations, as the subjects experienced a journey that was close to reality due to the reproduction of real traffic scenarios involving different transport modes. This experience was widely different than what could be obtained through SP surveys where two-dimensional images and text are presented.

According to Górski (2017), the main obstacle to VR being commonly implemented is that most solutions are specific, that is, created only for the purpose of the current context. This would require substantial time and high costs. Meanwhile, the advantage of our research is that, although it is true that the videos were recorded following the design specifications for the specific investigation, they could be used for other investigative purposes, for instance, to examine other parameters or latent variables in the same context. Furthermore, other researchers can follow the methodology.

Nevertheless, the cost of VR exercises can be considered a disadvantage of this technique since the scenes presented to the respondents involves several hours of recording to display the required scenarios and travel situations. As far as the execution of the experiment is concerned, the time required from each respondent is also high along with the additional time for visualising the videos (in this case, 10–15 minutes per scenario).

Despite the length of time that may be considered to execute the VR experiment, it will always be less than what must be invested if respondents were to conduct real trips, which have implications in terms of risk exposure, a situation, which, as mentioned above, should be addressed by the investigation.

The duration of exercise can also be considered as an important limitation because of the risk of respondent fatigue. In our case, this condition was mitigated by introducing a pause in the experiment. After watching each video (for instance, E1D), a respondent would answer questions associated with the choice of mode in this video as well as perceptions of the route, in the same way for the other videos (E1N, E2D and E2N).

According to Kuze and Ukai (2008), eye fatigue can be determined through objective and subjective indicators. Our research did not directly measure fatigue, but its effect was controlled by monitoring aspects such as eye soreness, headache and tiredness, which were not present in the participants. Future research may include objective measurements of fatigue indicators.

Sample selection was adjusted to the profiles of travellers who travel to the study area daily, according to the Origin Destination Survey (ODS). This means the results of this research can be generalised to populations that maintain the established distribution of travellers.

Sample size was directly related to the amount of time required by each experiment, and the costs were associated with the implementation of a greater number of experiments, which can be considered as further limitations of this research. However, the number of respondents was statistically suitable.

Finally, Bogacz et al. (2020) argued that the ecological validity of immersion technologies, the implementation of which in transport studies is recent and gaining popularity, has not yet been established; therefore, the use of these techniques in modelling human behaviour in transport has been limited. In

their study, they showed that participants behave differently when confronted with a choice between immersive and nonimmersive environments. The research results indicated that immersive environments can increase levels of commitment to tasks. Meanwhile, Brookes et al. (2018) indicated that VR helps increase ecological validity. Likewise, studies by Farooq et al. (2018) and Moussa et al. (2012) in the context of transport, Frankenhuys et al. (2010) and Underwood et al. (2011) on transport risk, Erath et al., (2017) on urban design and Patterson et al. (2017) on social context have shed light on generating real behaviour in traffic situations despite the lack of consequences.

For future research, we propose the development of a comparative study between two different environments in two different cities to evaluate security as a latent variable. Other studies could also investigate other latent variables such as comfort, reliability of travel time and fare affordability.

## 6. Conclusions

We proposed the use of VR as a safe and flexible instrument to capture reliable primary data for transport research. In this paper, we used VR to assess the effects of security perception on transport mode choice. Perception of security was approached from three constitutive elements: environment, subject and mode. VR allowed us to isolate the effect of each element and apply multiple combinations of their variants in a sample of 92 participants. Our contribution lies in the testing of the use of VR-based experiments with real urban scenario recordings in transport research and the capturing of on-experiment participant behaviour as rich data for mobility and transport public policy design.

Using VR, we recreated real journeys with six different transport modes considering variations in security perception elements and urban conditions. We recorded 360-degree immersive videos from real scenarios in Medellín, capturing daily urban life and compiling images in 3D along with their natural sounds. Video planning was conducted considering Agudelo's (2019) focus-group and social cartography findings on security perception determinants. The experiment considered two environments, secure (E1-active, illuminated, etc.) and insecure (E2-homeless presence, nonpermeable enclosures, etc.) and studied the effects of lighting conditions in the daytime (D) and night time (N). A total of four

videos (E1D, E1N, E2D and E2N) in tandem with the six transport modes were assessed by 92 participants.

We found that using real scenarios in a VR-based experiment in transport research allows for a realistic assessment of multiple and simultaneous journey conditions (and their possible combinations), overcoming the limitations of SP and RP surveys. VR videos improved the participants' experience, enabling close-to-natural sensorial immersion and assessment as opposed to computer-simulated environments. This method capitalised on participants' assessment of their preferred transport mode immediately after taking the virtual trip, as their emotions, sensations and perceptions were still active. This represents a significant advantage in front-to-static and memory-based or hypothetical survey experiments (SP and RP). In SP surveys, participants forecast their behaviour through a hypothetical journey that they might never have experienced, while VR-based experiments provide them close to real trip experiences and enable them to gauge their choices.

VR-based experiments allow for the evaluation of multiple conditions, in which researchers test several transport modes in different environmental conditions and consider various subjects' features. This technique enables the assessment of overall options set by the same subject despite never having been exposed to them. VR experiments capture participants' movements, gestures and expressions while taking virtual journeys as additional sources of information for mobility and transport public policy formulation. This technique also reduces participants' physical risk, a relevant ethical consideration in transport mode research. The structuring of scenarios from real city scenes, presented to participants through VR, allows the researcher to include/exclude elements whose effects they intend to evaluate. We evaluated multiple trip conditions: secure and insecure surroundings, six transport modes and daytime and night-time trips. In the case of secure and insecure surroundings, we included the presence of the homeless, activity of street vendors, nontransparent enclosures, busy places (active) and driving conditions. This combination was achieved with VR and is not offered by traditional techniques. VR helps users understand better the conditions associated with modes and environments.

The study sought to determine the incidence of three elements in the perception of security (environment,

subject and mode), in which it was necessary to isolate the effects of one to identify those of the others. VR made it possible to cover the latter situation and to combine and analyse the proposed elements. This was in line with Brookes et al. (2020), who indicated that VR reduces barriers to research in real rather than laboratory environments.

The VR exercise opens windows for a detailed study of phenomena, in which the territorial–subject relationship is presented. The use of cross-sectional data is predominant in transport studies given the limited access to panel data. This requires starting with samples of considerable size, such that, over time, the decrease in sample size can be compensated by the difficulty of preserving the same group because of participant withdrawal. VR experiments can be used to collect panel data with a reduced number of participants and assess the same virtual journeys and environmental setups. Panel data collected from these conditions enable the further elaboration of the effect of familiarity with the environment on transport mode choice and the impacts of changes in psychological conditions on transport decision-making. This will enable the design of public policies that address aspects determining security in the three elements proposed in this research: environment, subject and mode.

Given this study's exploratory nature, the experimental design did not consider the time and cost of the trip in the participants' decision-making since these variables have been widely studied and reported in the literature. Subsequent studies may include these variables in the scenario of choice, as well as others considered relevant in the choice of transport mode, the impact of which must be determined.

#### Disclosure statement

The authors declare no conflict of interest.

#### Author Contributions

The authors confirm the contribution to the paper as follows: study conception and design: Agudelo-Vélez, Sarmiento-Ordosgoitia and Córdoba-Maquilón; Data collection: Agudelo-Vélez and Sarmiento-Ordosgoitia; analysis and results interpretation: Agudelo-Vélez and Sarmiento-Ordosgoitia; draft manuscript preparation: Agudelo-Vélez. All authors reviewed the results and approved the final version of the manuscript.

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