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Pedestrian Crossings as a Means of Reducing Conflicts between Cyclists and Pedestrians in Shared Spaces

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Abstract: One significant and simultaneously interesting problem in urban mobility has to do with the study of shared spaces where various categories of users coexist and act together. This paper aims to examine the behavior and preferences of pedestrians and cyclists, who both coexist in a shared space infrastructure along the seafront (which has a length of around 4.0 km) of the city of Thessaloniki, Greece. Furthermore, the problems caused by the coexistence, such as at the locations where there are pedestrian crossings on the bicycle lane, are recorded and evaluated. Traffic calming measures aimed at improving the existing situation in terms of safety and comfort for both pedestrians and cyclists are also explored. Data were collected through a web-based questionnaire survey, which was distributed via email to students and employees of Aristotle University of Thessaloniki. A total of 1194 questionnaires were collected in the framework of the survey during the year 2021, including responses from both pedestrians and cyclists. The questionnaires were analyzed through the use of descriptive and inferential statistics; the latter method suggested several significant differences in how each group of users (pedestrians or cyclists) perceived their behavior compared with the other. Latent variable and path models were estimated to investigate the behavior and attitude of users towards the crossings, examined as a function of their perception towards the other group; perception about the benefits of the infrastructure; preference for additional interventions; and overall opinion about the quality of the shared space area. The results suggest that forms of aggressive behavior, preference towards using the crossings, and the perceived safety are affected by the aforementioned factors. The results of this study can inform decision takers and decision makers in the area of land use regarding policy recommendations for facilitating interactions between pedestrians and cyclists in shared spaces.

Keywords: vulnerable road users; cyclists; pedestrians; shared space; urban road safety; pedestrian crossings

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1. Introduction

The concept of shared streets and spaces, where different categories of users share a single infrastructure, is not a recent idea. In fact, streets have historically been a location for people to interact, a place where social, cultural, and economic activities of cities have taken place [1]. The advent of motor vehicles and subsequent growth of the automotive industry in the past century have presented novel challenges for transportation and urban planning. The primary objective has been to cater to the increasing volumes of motorized traffic and enable the faster movement of vehicles. These objectives and the respective policies have led to the formation of separate lanes for each road user category and to the allocation of more space to motorized vehicles rather than to active modes [2].

Transportation planners and policy makers have come to realize in recent times that creating separate lanes for each type of road user is a daunting task due to the scarcity of public space [3]. Furthermore, they have come to acknowledge the importance of enhancing the street's role in facilitating social interactions [1]. As of now, there is a trend towards reallocating urban space in a manner that prioritizes pedestrians and other forms of sustainable transportation while also transforming streets into hubs of social activity and human interaction. This is evidenced by the most recent edition of the Sustainable Urban Mobility Plans guidelines [4]. To this effect, cities are increasingly adopting shared infrastructure for pedestrians and bicycles.

Numerous studies have been conducted to determine the safety and desirability of pedestrian–cyclist coexistence and shared infrastructure compared with situations where cyclists share the road with motorized vehicles. Aultman-Hall and LaMondia conducted one of the initial research studies that examined the safety of shared infrastructures for pedestrians and cyclists [5]. The authors utilized a questionnaire survey to gather data on accidents and exposure, which allowed them to calculate indicators for three infrastructure types located in the United States. The findings indicate that falls are the most common type of accident in the shared pedestrian–cyclist infrastructures, whereas collisions between pedestrians and cyclists are infrequent [5]. Chong et al. conducted a study using the mortality data for New South Wales from the Australian Bureau of Statistics, as well as injury data from all public and private hospitals in the state [6]. Their aim was to compare the severity of collisions between bicycles and motor vehicles with those between bicycles and pedestrians. After conducting a statistical analysis, Chong et al. concluded that the risk of injury is greater for cyclists who are involved in collisions with motor vehicles, but collisions between bicycles and pedestrians can also result in severe injuries. Moreover, the study found that the risk of serious injury is higher for pedestrians and cyclists who are aged over 65 years [6]. An additional research effort tried to assess the risk of injury or fatality resulting from pedestrian–bicycle collisions; the findings indicate that the probability of death is negligible, while the likelihood of injury is as infrequent as the probability of death in a plane crash [7].

A study conducted in Melbourne, Australia, examined pedestrian injuries resulting from collisions with bicycles from 2006 to 2016 [8]. The study found that there was no increase in such injuries during this period and that the frequency of these injuries was significantly lower than the frequency of pedestrian injuries resulting from collisions with motor vehicles [8]. Varnild et al. conducted a comprehensive analysis of pedestrian and cyclist injuries in Sweden from 2003 to 2017, which was during the time that the "Vision Zero" road safety policy was implemented [9]. The authors found that injuries to both pedestrians and serious injuries to cyclists were significantly less common outside of the road where there was no interaction with traffic, and they recommended the separation of unprotected road users from motorized traffic. Aligned with the above conclusions are the results of the study by Soleil Cloutier et al. (2022), which set up a pilot project for allowing bike riding in a pedestrian street and monitored users' behavior and conflicts; the authors stated that the co-existence of pedestrians and cyclists only poses a few risks to users' safety [10].

Except for the abovementioned studies that use data about injuries and collisions, important indications about how safe the co-existence of pedestrians and cyclists is can be provided by questionnaire surveys that examine users' perceptions and attitudes. Kang and Fricker (2016) analyzed responses with respect to some recorded videos from shared infrastructures in China and concluded that the opinion of pedestrians about infrastructures where co-existence with cyclists is required tends to be negative; however, this negative attitude can be moderated if sufficient space is allocated to pedestrians and if speed restrictions for cyclists are set [11]. The issue of space allocation and cyclists' speed moderation has also been discussed by other studies. A study that was conducted in Thessaloniki, Greece, identified that over-dimensioning a bicycle lane in pedestrians–cyclists shared infrastructure has a negative impact on pedestrians' perceptions regardless of the cyclists' flows [12]; meanwhile, a study in Bristol concluded by stating that moderating cyclists' speed is essential for improving pedestrians' perceptions [13]. Some interesting points have been raised by the study of Hatfield and Prabhakharan (2016). Their analysis identified that an important issue for cyclists is that they fail to adequately supervise children or animals, while an issue that pedestrians face is that cyclists do not warn when they are about to pass [14]. A more recent study by Gkekas et al. (2020) highlighted that a high number of pedestrians and cyclists have experienced traffic conflict in shared infrastructure, which leads to cyclists avoiding areas where increased interactions with pedestrians exist [15].

Despite the limited number of serious injuries that have occurred from cyclist and pedestrian collisions, it has become understood that safety issues still exist, and the design of spaces where these two categories of users co-exist continues to be challenging [16,17]. To improve safety in pedestrian–cyclist shared spaces, several measures can be implemented. These measures mainly aim to reduce the conflicts and events between the users which, according to previous studies, have been shown to have an important effect on users' perceptions and result in a deteriorated perceived quality of service [18–20]; they are mostly experienced in cases of high traffic volumes and traffic complexity [21]. One of the most effective measures is to create clearly marked paths for each mode of transportation. This can include separate bike lanes and pedestrian walkways, each with their own unique markings and signage. Additionally, speed limits can be lowered to reduce the risk of accidents, and appropriate lighting can be installed to improve visibility, especially during nighttime hours. Other measures include the use of warning signs and pavement markings to alert cyclists to the presence of pedestrians. In cases where users have limited experience with pedestrian–cyclist co-existence, such measures are even more important, as the limited experience can result in a negative assessment of the infrastructure and confrontations between the users, therefore leading to an unwillingness to use the specific infrastructure [22,23].

The present paper aims to assess the performance of a measure that has rarely been applied internationally in practice. More specifically, this paper assesses how crosswalks in the form of zebra crossings within a bicycle lane affect not only the perceptions, but also the behavior of both cyclists and pedestrians in shared spaces. Because such a measure has only been used in limited cases worldwide, its assessment is considered essential; moreover, the assessment can provide evidence about whether this measure can be efficient for improving safety conditions in areas where high flows of cyclists and pedestrians are being concentrated. Focusing on the implementation of the pedestrian crossings as the main point of interest, we attempt to unravel the behavior and attitude of users regarding this measure, specifically with respect to their attitudes towards the other group of users and with respect to their perception about the shared space overall, including preferences for additional interventions. To this end, we have developed a conceptual framework for investigating the aforementioned issues. This framework was specified and estimated in the form of latent variable and path models for both pedestrians and cyclists. For the purposes of our research, we collected data via a questionnaire survey that was administered online. To the best of our knowledge, there is no other quantitative study that has aimed to holistically assess pedestrian crossings in bicycle lanes; therefore, the results of this paper can not only guide researchers, but also practitioners and authorities.

The remainder of the paper is organized as follows; Section 2 presents the area of our case study and the details of the questionnaire survey data collection. This is followed by Sections 3 and 4, which present some preliminary descriptive and inferential statistics analysis for providing a better understanding of the collected data. Section 5 presents our conceptual framework; this is followed by Section 6, which focuses on the modelling approach and results. This paper concludes with a Section 7.

2. Materials and Methods

2.1. Case Study

Thessaloniki is located in northern Greece. According to the latest data from the Hellenic Statistical Authority, the city's permanent population stands at 1,091,424; out of the permanent population, women comprise 52.5% (573,228) and men comprise 47.5%

(518,196). The transport system in Thessaloniki includes a comprehensive bus network, and a metro system is expected to start its operation in the beginning of 2024. Furthermore, some micromobility services exist [24,25]. Thessaloniki's Sustainable Urban Mobility Plan states that 41.3% of trips in the city are made using private cars, while public transport and motorcycles make up 33.7% and 11% of the modal share, respectively. However, the use of active modes of transportation such as walking and cycling is relatively low, accounting for only 9.2% and 1.7% of the modal share, respectively [26].

The most popular place for cycling in the city of Thessaloniki is the seafront area, where a bicycle lane runs parallel to the waterfront; this offers cyclists a comfortable and scenic route. The bicycle lane is well-marked and separated from vehicular traffic, making it an enjoyable experience for cyclists of all skill levels. The lane is also wide enough and mainly accommodates recreational cyclists. The seafront area also provides a great pedestrian-friendly environment for citizens and visitors of Thessaloniki. A spacious pedestrian promenade runs parallel to the bicycle lane and offers a great place for a leisurely walk or jog.

However, in the seafront area, the high levels of pedestrian and cycling flows, especially during weekends, result in conflicts between pedestrians and cyclists, which raises safety concerns. These concerns became even greater since the growth of micromobility vehicles. Following these issues and for the further designation of the areas that are provided for walking compared with those that are provided for cycling, horizontal signage has been added by the local authorities. Actually, pedestrian crossings, as shown in Figure 1, were painted for reducing the conflict points between cyclists and pedestrians and for alerting both user categories.

Figure 1. Pedestrian crossing in the bicycle lane of the seafront area.

According to Hamilton-Baillie [1,2], shared spaces are characterized by two main elements: the minimization of segregation between users and the reliance on mutual respect. These two elements are applicable in the seafront area, as segregation between cyclists and pedestrians exists; however, this does not include any physical elements, and the harmonious co-existence of users heavily relies on mutual respect. Moreover, the specific area can be considered as a destination place that mostly attracts people for recreational purposes, which is an additional attribute of shared spaces. In this sense, we characterize the seafront area as a shared space, even if an indication about space allocation exists.

2.2. Data Collection

To investigate the behavior of the users in the bicycle lanes' crossings and assess the performance of this measure, a questionnaire survey was carried out. At first, the questionnaire was designed; the questionnaire included four different sections. The first section includes questions that are related to both the socioeconomic profile of the respondent as well as the experience of the respondent with respect to the use of the seafront area, i.e., the main travel purpose when using the seafront and frequency of using it as a pedestrian and cyclist. The second section follows the point of view of a pedestrian and includes questions regarding the choice to use the crossings, the perceptions of it, and the assessment of cyclists' behavior when a pedestrian is using the crossings. The third section includes similar questions to the second one, but follows the point of view of a cyclist. In the fourth section, the respondents are asked to provide an assessment of the crossings with respect to safety and flow improvement. It should be noted that if the respondent was more frequently using the seafront as a pedestrian, they were asked to answer the second section of the questionnaire but not the third one; if they were mostly using it as a cyclist, they were asked to answer the third section but not the second one. This way, each respondent participated from the perspective in which they mostly experienced the infrastructure.

The questionnaire was designed in an electronic format and was distributed within the community of the Aristotle University of Thessaloniki by email to all registered members (i.e., both students and employees). This approach was selected due to the COVID-19 constraints and to reach a greater sample, as the university community has been found to be keener in responding to such surveys. A total of 1194 questionnaires were successfully completed, and they were used for the statistical analysis; from the responses, 1059 were from people that mostly used the seafront as pedestrians and 135 were from people that mostly used it for cycling.

3. Descriptive Statistics

3.1. Participants

Out of the overall sample (1194 respondents), 60.2% of respondents were female, 37.6% were male, and 2.2% did not wish to state their gender. With respect to age, 71.3% of respondents were 18–24 years while 21.2% were 25–39 years old. Regarding the other age groups, 6.4% of respondents were 40–54 years old and 1.2% were 55–64 years old. These findings suggest that our sample consisted of younger individuals. This potential bias towards younger respondents was potentially due to the fact that the survey was administered online and was also circulated within university-related means. The latter is further supported by the respondents' occupation, as 80.7% of respondents were university students. In the question regarding what type of user the respondents would identify themselves as, 88.7% stated that they were pedestrians and 11.3% identified as cyclists.

The study area itself is mainly a leisure infrastructure; this fact was also reflected in the listed trip purpose of the users, where 81% of respondents reported that they used the shared space for leisure/walking. This was followed by physical activity (12.7%), while other activities represented the remaining responses. More than half of the respondents (51.26%) never cycle at the infrastructure, and 72.9% walked at the area at least once a week (14.7% stated daily use). However, when focusing on respondents identifying themselves as cyclists, approximately 30% of respondents use the infrastructure daily, whereas approximately 41% use it more than once a week. That is, the cyclists of the sample are on average very familiar with the infrastructure.

Overall, the respondents were satisfied with the quality of the infrastructure as expressed in terms of cleanliness, safety, comfort, and aesthetics. Moreover, the implementation of pedestrian crossings was in general well-received as it was more perceived as helping with user interactions rather than interrupting their flows. Following this positive perception, it is very interesting that 72.11% of respondents stated that they would use the infrastructure more after the implementation of interventions. All suggested interventions (e.g., physical separation, better lighting conditions, different coloring of the bike lane, different surface material for the bike lane, additional signs at the pedestrian crossings) were considered to be very important or important, with the exception of moving the bicycle lane to a different location.

3.2. Pedestrians and Infrastructure

Out of the 1059 pedestrian respondents, 23.9% responded as having not ever noticed the existence of pedestrian crossings on the cycling lane. Additionally, although only 3.3% of respondents reported a collision with a cyclist, 46.2% mentioned a near miss, which is an expected finding because of the former being less likely to occur. There was not a clear trend regarding the perception towards sharing the space with cyclists, as the pedestrians' responses were split across different levels of agreement; however, there was a higher tendency to agree with the arrangement.

Regarding the pedestrian crossings, there was not a clear outcome observed regarding their choice for crossing the cycle path. However, when using the crossings, approximately 75% of respondents stated that they checked for oncoming bicycles before crossing. Moreover, pedestrians were positively inclined with respect to the perception of safety when using the crossings, and most pedestrians stated that they do not react with anger when a cyclist does not give them priority to cross.

Most pedestrians agreed that cyclists respect the boundaries of the bicycle lane. However, their perceptions mostly range from neutral to negative regarding cyclists decreasing their speed when they attempt to cross using a pedestrian crossing. The same also applies regarding cyclists giving priority to pedestrians and reacting with anger when pedestrians attempt to cross without the presence of a pedestrian crossing. However, lower levels of cyclist anger were reported for interactions that took place at a pedestrian crossing.

3.3. Cyclists and Infrastructure

Out of the 135 cyclists' responses, 90.4% reported that they observed the pedestrian crossings, which is a higher proportion compared with pedestrians. Moreover, 12.6% reported a crash with a pedestrian, while 71.9% reported a near miss. These are also higher levels, compared with the pedestrians' responses. Like pedestrians, there was not a distinct pattern with respect to the perception of cyclists for sharing space with the former user type.

The majority of cyclists (57.8%) totally agreed with respect to the statement of reducing their speed when a pedestrian was at a pedestrian crossing. Similarly, most cyclists reported giving priority to pedestrians and higher levels of reacting with anger when pedestrians crossed the bike lane without the presence of a pedestrian crossing. There was not a clear trend in the level of agreement regarding the additional safety by the pedestrian crossings. Cyclists agree that pedestrians do not respect the boundaries of the bicycle lane, and the cyclists do not agree that pedestrians choose the pedestrian crossings or check for oncoming bicycles while crossing.

4. Inferential Statistics

Before the modeling exercise, the responses of pedestrians and cyclists were compared to obtain a better understanding of the potential differences in how the two groups perceive each other. Given the ordered nature of the examined questions, the Wilcoxon rank sum test with continuity correction was used. The test only provides the p-value that is related to the significance; hence, the direction of the differences in responses was examined via the mean and median values. Some of the most notable findings are presented in the following subsections.

4.1. Users and Infrastructure

The responses of pedestrians and cyclists did not significantly differ with respect to sharing the infrastructure with each other; in general, there is a neutral opinion from both sides. Cyclists stated that they feel significantly less safe by the presence of pedestrian crossings ($W = 63{,}662$, $p = 0.034$), which may indicate that the infrastructure is more well-received by pedestrians. On the other hand, pedestrians are of the opinion that cyclists move outside the bike lane to a greater extent compared with cyclists perceiving pedestrians walking in the bike lane ($W = 45{,}158$, $p < 0.001$). It is interesting that despite the majority of pedestrians stating that they are carefully checking before crossing the bike lane, the opinion of cyclists is significantly different regarding the matter (W = 33,200, $p < 0.001$). Moreover, cyclists disagree to a greater extent that pedestrians choose the pedestrian crossings to walk through the bike lane (W = 36,999, $p < 0.001$). Cyclists also perceive pedestrians as reacting with anger more compared with what pedestrians reported about themselves (W = 84,614, $p < 0.001$). No significant difference was found regarding the reaction of cyclists in the event of a pedestrian crossing the bike lane. On the other hand, pedestrians disagree significantly more that cyclists reduce their speed when the former group is trying to cross the bike lane by using the pedestrian crossing (W = 106,788, $p < 0.001$). The same pattern was observed with respect to cyclists giving priority to pedestrians from the perspective of when the latter group is waiting at the pedestrian crossing (W = 98,677, $p < 0.001$).

4.2. Attitudes towards Infrastructure

The respondents were asked about a series of quality-related elements regarding the infrastructure, namely comfort, safety, aesthetic of the environment, and cleanness. No significant differences were found for these indicators except for the latter (W = 79,822, $p = 0.022$). Pedestrians disagree more regarding the cleanliness of the infrastructure; however, this observation is unlikely to be related to their interactions with cyclists. With respect to the implementation of the pedestrian crossings, pedestrians agree to a greater extent on the crossings provide more safety (W = 56,085, $p < 0.001$) compared with cyclists. Similarly, the former group agrees more that pedestrian crossings allow for easier interactions between the users (W = 61,042, $p = 0.004$). Pedestrians also had higher levels of agreement regarding the improvement of cyclists' flows due to the pedestrian crossings (W = 63,398, $p = 0.025$), whereas the opposite was found with respect to the disruption of flow (W = 82,101, $p = 0.003$). No significant differences were observed, however, between the two groups of users regarding the improvement or decline of pedestrians' smooth flow. Finally, the respondents were asked about a series of potential interventions that could be implemented to the infrastructure. No significant differences were observed regarding any of the interventions, except for the change in surface material for the bike lane; cyclists agreed more regarding this intervention (W = 91,056, $p < 0.001$).

5. Conceptual Framework

5.1. Variables

The variables of the survey were arranged in a number of groups that we considered in our analysis. These groups were:

- User's background: this group of variables refer to the background of the respondents and their past experience with the other group of users, particularly regarding any occurrence of a crash or near miss.
- Behavior of the other group: this concept refers to how a group of users perceives the behavior of the other group in their interactions at the infrastructure under study.
- Perceived quality of the infrastructure: this concept represents the general perception of a group of users regarding the overall quality of the infrastructure.
- Perception about pedestrian crossing: this group of variables captures the overall perception of a group of users regarding the efficiency of the pedestrian crossing.
- Interventions: this group represents the opinion of the respondents towards the implementation of specific interventions.
- Behavior of a group of users regarding the pedestrian crossings.

These groups of variables were considered in the development of a conceptual framework that would unravel the relationships between the attitudes of users about the infrastructure, the pedestrian crossings, their opinion about the other users and, ultimately, their behavior.

5.2. Factor Analysis and Latent Constructs

Prior to the estimation of the models that reflect our conceptual framework, a series of factor analyses was performed to examine the validity of the constructs used. In particular, we examined every group of questions using an exploratory factor analysis (EFA) to confirm whether the examined items (questions) were part of the same factor or if they were part of multiple factors. The results, including the expected factor and outcome after performing the EFA, are presented in the Appendix A in Tables A1 and A2 for the pedestrians and cyclists, respectively. In both tables, the factor loading values refer to the values along with the factor that each item was most related unless otherwise indicated. It should be mentioned that the variables in the two tables were not all examined simultaneously. The EFA was performed separately to each of the original groups in order to confirm our a priori expectations regarding the relevance among the questionnaire items of specific blocks of questions. Additional factors were then generated based on the results of the EFA for each group of questions.

Among the most interesting outcomes regarding the EFA analysis that was applied on the pedestrian sample, it is worth mentioning that our questions in the theme of Pedestrian and pedestrian crossings infrastructure were grouped into two categories: behavior at the pedestrian crossings, which includes items regarding pedestrians' behavior and reactions when using the pedestrian crossings; and attitudes towards using the pedestrian crossings. In the next general concept of the perceived cyclists' behavior when interacting with pedestrians at the bicycle lane, the items were grouped in two concepts, namely, cyclists' behavior and cyclists' anger. Moreover, the items related towards the perception of the pedestrian crossings in general were grouped into those related to the positive effects of pedestrian crossings in interactions and negative effects of pedestrian crossings in interactions. With respect to the implementation of interventions that could increase the use of the shared space infrastructure, two themes occurred: Soft interventions, which refer to measures that should be taken on the existing infrastructure/cycle lane; and Hard interventions, which refer to the implementation of physical separations or transportation of the bicycle lane to a different location. Finally, the general quality indicators of the infrastructure resulted in only one factor.

The cyclists' sample was considerably smaller; however, the EFA that was applied in the same manner as the pedestrians' sample suggested comparable results. In particular, regarding the pedestrians' behavior, two factors were extracted of which one could be related to pedestrians' anger. One difference compared with the pedestrians' sample regarding the perception towards the pedestrian crossings was found: although one factor was about the positive impact of pedestrian crossings, the second was related to the impact of pedestrian crossings on the flow of bicycles rather than the negative impact of the measure on both users' flows. Although the perception regarding the improvement of cyclists' flows had a higher loading on the latter factor, it also had a comparable value with respect to the positive impact factor. Another difference was related to one of the intervention items: although the hard intervention-related items were part of the same factor (as in the pedestrians' sample), one additional item was also related to this factor, specifically the different coloring of the bicycle lane. Finally, all items that were related to the perceived general quality of the infrastructure were part of the same factor.

5.3. Proposed Conceptual Framework

Our conceptual model was based on the idea of unravelling the stated behavior of pedestrians and cyclists with respect to the use of the pedestrian crossings. Moreover, by considering the stated behavior and overall attitudes towards the shared infrastructure, we aim to understand whether it would be possible to increase the use of the infrastructure. Based on the initial groups of variables and the constructs generated as part of the EFA analyses, the conceptual framework was developed as follows:

- Level 1: the perceptions of users that may drive their opinion about the infrastructure, the other group of users, and their interactions. An example is the perception about sharing spaces in general.
- Level 2: in this level, we considered the overall perception about the quality of the infrastructure under investigation.

- Level 3: in the first layer of this level, we considered the perception about the behavior of the other group of users under the presence of pedestrian crossings. We assume that this perception, together with the variables from the two previous levels, is what then affects the opinion about the usefulness of the pedestrian crossings in facilitating interactions.
- Level 4: here, we included the preference for the implementation of potential new interventions as a function of the variables from the previous levels.
- Level 5: in this final level, we examined the behavior of a group of users around the pedestrian crossings, their general feelings towards pedestrian crossings, and the potential of increasing the use of the infrastructure as a function of these two factors combined with the variables from the previous levels.

6. Results

6.1. Model Specification

Our conceptual framework was implemented for the pedestrians' sample in the form of a structural equation model. This approach was selected given that the EFA analysis suggested several factors that were ultimately implemented as latent variables. Structural equation models (SEMs) are composed of two main parts. The latent variable model captures the relationship between endogenous (dependent) and exogenous (independent) latent variables. The measurement model reflects the impact of latent variables on the observed variables (indicators). The main formula (Equation (1)) of a SEM is

$$\eta = B\eta + \Gamma\xi + \zeta \quad (1)$$

where η is an $(m \times 1)$ vector of the endogenous variables, ξ is an $(n \times 1)$ vector of the exogenous latent variables, and ζ is an $(m \times 1)$ vector of the random disturbance. The m and n indicators indicate the number of the endogenous and exogenous latent variables. The elements of the B and Γ matrices are the parameters of the model. The B matrix is an $(m \times m)$ parameter matrix of the latent endogenous variables, and the Γ matrix is an $(m \times n)$ parameter matrix for the latent exogenous variables. The main formulae of the measurement model are

$$x = \Lambda x\xi + \delta \quad (2)$$

for the exogenous variables (Equation (2)) and

$$y = \Lambda y\eta + \varepsilon \quad (3)$$

for the endogenous variables (Equation (3)), where the observed variables are indicated by the vectors y $(p \times 1)$ and x $(q \times 1)$. The p and q indicators denote the number of the endogenous and exogenous indicator (observed) variables, respectively. The matrix Λy $(p \times m)$ reflects the parameters of the y elements, while the matrix Λx $(q \times n)$ indicates the parameters of the x elements. The measurement errors for y are indicated by the $(p \times 1)$ vector ε and for x by the $(q \times 1)$ vector δ.

Although the same sets of variables were available both for the pedestrians' and cyclists' samples, the latter had a considerably smaller sample size. Because of this, we followed a more simplified approach. That is, rather than considering latent variables, we implemented a path model where the items' values that composed each factor of the cyclists' sample were averaged. These simpler average values were then used as the model input. Both models were estimated using the diagonally weighted least square method, which is more robust for categorical or non-normal variables, using the lavaan (v 0.6.12) [27] package of R software [28].

6.2. Results for Pedestrians

The results of the pedestrians' model are presented in Table 1. The measurement equation model results are presented in Table A3 of the Appendix A. The item codes in

Table A3 correspond to those presented in Table A1. The goodness-of-fit indices presented in Table A4 of the Appendix A suggest a moderate but acceptable fit. Starting from the more generic aspects of pedestrians' perceptions, the general attitude towards sharing the infrastructure with cyclists had a negative association with reporting a near miss with a cyclist. That is, having a negative experience with a cyclist was negatively related to sharing space with the latter. The attitude towards sharing was positively related to the perceived overall quality of the infrastructure. Hence, pedestrians who do not agree with shared space are also less likely to attribute qualities such as comfort or safety to the infrastructure. Older respondents were more likely to perceive the infrastructure as of lower quality. Older individuals as well as those who reported a near miss with a cyclist were also less likely to hold a positive opinion towards the positive behavior of cyclists when interacting with pedestrians at the bicycle lane. The perception about the positive impact of pedestrian crossings was related to the general perception about the quality of infrastructure and the perception towards cyclists' behavior. In the next level of the model, the variables related to the general perception towards the infrastructure, cyclists, and pedestrian crossings were used to investigate their relationship with preferred interventions that could increase the infrastructure's use. The preference for soft interventions were positively related to the positive perception about the pedestrian crossings and attitude towards sharing the space with cyclists. On the other hand, a positive perception regarding the general quality of the infrastructure was negatively related to the preference for the implementation of soft interventions. With respect to the preference for the implementation of hard interventions, the same outcomes are observed with respect to the perception of the pedestrian crossings, the overall quality of the infrastructure, and the perceived efficiency of the pedestrian crossings. Moreover, the preference for hard interventions was negatively associated with the perceived positive behavior of cyclists in interactions at the bike lane. Pedestrians who perceive such behavior to a lesser extent are more likely to prefer the implementation of hard interventions, i.e., physical separation or moving the infrastructure to a different location. The final level of the model regards the impact of both the general perception and the specific perception about the pedestrian crossings of pedestrians on their behavior and preference for the latter. Pedestrians were more likely to report negative behavior (indicated by not checking for bicycles before crossing or expressing anger) if they did not share a positive attitude towards the behavior of cyclists in their interactions or towards the efficiency of the pedestrian crossings, preferred the implementation of hard interventions, or did not agree with the shared space. Pedestrians' preference for pedestrian crossings was related to the perception about cyclists' behavior and the positive effects of implementing the pedestrian crossings. Finally, the positive effects of implementing the pedestrian crossings and the preference for the implementation of both soft and hard interventions was positively associated with the increased use of the infrastructure.

Table 1. Structural model parameter estimates—Pedestrians' model.

Paths			Estimate	z-Value	*p*-Value
Perception towards sharing space	←	Near miss with a cyclist	−0.25	−3.60	0.000
Overall quality	←	Perception towards sharing space	0.26	12.31	0.000
Overall quality	←	Age: 18–24	−0.17	−3.52	0.000
Perceived cyclists' (positive) behavior	←	Near miss with a cyclist	−0.21	−4.14	0.000
Perceived cyclists' (positive) behavior	←	Age: 18–24	−0.28	−4.77	0.000
Positive effect of pedestrian crossings	←	Perceived cyclists' (positive) behavior	0.18	8.11	0.000
Positive effect of pedestrian crossings	←	Overall quality	0.17	9.87	0.000
Soft interventions	←	Positive effect of pedestrian crossings	0.39	15.63	0.000
Soft interventions	←	Overall quality	−0.20	−8.48	0.000
Soft interventions	←	Perception towards sharing space	0.09	4.24	0.000
Hard interventions	←	Perceived cyclists' (positive) behavior	−0.87	−4.10	0.000
Hard interventions	←	Positive effect of pedestrian crossings	0.88	3.94	0.000

Table 1. *Cont.*

Paths			Estimate	z-Value	*p*-Value
Hard interventions	←	Overall quality	−1.11	−4.07	0.000
Pedestrians' (negative) behavior	←	Perceived cyclists' (positive) behavior	−0.50	−7.16	0.000
Pedestrians' (negative) behavior	←	Hard interventions	−0.32	−3.83	0.000
Pedestrians' (negative) behavior	←	Positive effect of pedestrian crossings	0.30	5.64	0.000
Pedestrians' (negative) behavior	←	Perception towards sharing space	0.24	6.72	0.000
Attitudes towards using the pedestrian crossing	←	Perceived cyclists' (positive) behavior	0.18	6.05	0.000
Attitudes towards using the pedestrian crossing	←	Positive effect of pedestrian crossings	0.38	12.16	0.000
Increased use after interventions	←	Positive effect of pedestrian crossings	0.03	2.10	0.036
Increased use after interventions	←	Soft interventions	0.09	7.68	0.000
Increased use after interventions	←	Hard interventions	0.05	4.06	0.000

6.3. Results for Cyclists

The results of the pedestrians' model are presented in Table 2. The goodness-of-fit indices presented in Table A4 of the Appendix A suggest a good fit. With respect to the overall perceived quality of the infrastructure, cyclists who did not agree with sharing the space with pedestrians were also more likely to perceive lower levels of quality. Moreover, female respondents were more likely to perceive an overall higher quality. A near miss with a pedestrian was negatively related to the positive perceived behavior of pedestrians when the latter cross the bike lane. The same observation was also made in the model of pedestrians. Another similar trend in the pedestrians' model was that the perceived overall quality was positively related to positive effects in interactions due to the presence of pedestrian crossings. The latter was negatively associated with the preference for the implementation of hard interventions. It should be mentioned that among the tested model specifications, the overall perception about the quality of the infrastructure was also positively related to the perception about the implementation of hard interventions. However, it was not possible to include in the model specification both the perception about the positive impact of pedestrian crossings and the overall perceived quality, as the direct effect of the latter was losing significance. It is likely that both variables are important, but our model was not able to capture these effects due to limitations in the sample size. The reported behavior of cyclists was negatively associated with the perceived positive behavior of pedestrians. That is, cyclists who perceived a negative behavior from pedestrians were also more likely to express behavior such as speed reduction or giving priority. Positive cyclist behavior was also related to the perception about sharing the road with pedestrians. These findings are consistent with the pedestrians' model. Among the various model specifications tested, the overall perceived quality of the infrastructure was positively related to the positive cyclists' behavior. However, this variable was losing significance if both this and the perception towards sharing were included (possibly given that their relation was already included in the model specification); hence, the overall perceived quality was dropped in the final model specification. It is possible that infrastructure that is not perceived to be of high quality (with sharing the space being one of the reasons for this) could trigger aggressive behavior to a greater extent. Regarding the preference for soft interventions, unlike the pedestrians' model, no significant associations were found. The inclination towards having a positive perception for using the infrastructure (reflected in the perception of safety alone) was related to the overall perceived benefits from the presence of pedestrian crossings. This finding is the same as the one obtained in the pedestrians' model. In the latter, however, the behavior of the other group of users also had a significant impact. Finally, the willingness to use the infrastructure more was related to the implementation of hard interventions. Overall, the two models are consistent; however, fewer significant relationships were found in the pedestrians' model, which could be attributed to sample size limitations.

Table 2. Structural model parameter estimates—Cyclists' model.

Paths			Estimate	z-Value	*p*-Value
Overall quality	←	Perception towards sharing space	0.22	4.17	0.000
Overall quality	←	Gender: Female	−0.40	−2.69	0.007
Perceived pedestrians' (positive) behavior	←	Near miss with a pedestrian	−0.67	−3.39	0.001
Positive effect of pedestrian crossings	←	Overall quality	0.29	3.77	0.000
Hard interventions	←	Positive effect of pedestrian crossings	−0.29	−2.76	0.006
Cyclists' (negative) behavior	←	Perceived pedestrians' (positive) behavior	−0.55	−3.99	0.000
Cyclists' (negative) behavior	←	Perception towards sharing space	0.23	3.21	0.001
Attitudes towards interacting with the pedestrian crossing	←	Positive effect of pedestrian crossings	0.57	3.42	0.001
Increased use after interventions	←	Hard interventions	0.09	2.04	0.041

6.4. Sample Size and Power Analysis

As reported in Table A4 of the Appendix A, the goodness-of-fit indices suggested a good fit of the models to the data. An additional test focuses on the sample size of the models, which is relevant especially for the cyclists' model due to the lower sample size. In general, there are no strict rules for sample sizes in SEM models so much as rules of thumb [29]. Another approach is to investigate the overall statistical power of a model with respect to a specific goodness-of-fit indicator (for instance, RMSEA) and with respect to Type II errors. For instance, a power analysis can be conducted to determine the sample size for an SEM model, which can detect the misspecification expressed as RMSEA $\geq$ 0.05; this is usually considered as the maximum acceptable value for a great model fit (or any other critical value) [30]. Except for this a priori power analysis, it is also possible to examine the achieved power of a model with respect to a given sample size and the degrees of freedom (post hoc power analysis). We conducted the aforementioned types of power analyses using the R package 'semPower' (v. 2.0.1) [31]. The results are presented in Table 3 where, for the given degrees of freedom (taken from our models' results), we conducted a priori and post hoc analyses for different levels of RMSEA accuracy. For the pedestrians' model, the required sample size was always smaller than what was available in the data sample size. Moreover, the post hoc model could be able to detect a misspecification expressed as RMSEA with a probability higher than >0.999 for all of the critical values of RMSEA tested. On the other hand, the cyclists' model would require a sample of 225 individuals to detect a power of 80% RMSEA $\geq$ 0.05. However, relaxing this to higher values (either 0.08 or 0.1) results in the required sample sizes being smaller than what is available in the data. This is further reflected in the post hoc analysis, where the power for detecting RMSEA $\geq$ 0.05 was only 0.49; however, this probability was above 0.95 for critical RMSEA values of 0.08 or 0.1. Hence, the cyclists' model could be benefited from an additional sample as it would help to detect even more significant relationships via the model; however, the current sample size is sufficient to ensure the detection of misspecification under a moderate fit.

Table 3. Results of the power analyses.

	Pedestrians' Model		Cyclists' Model	
RMSEA	**Sample Size (A Priori)**	**Power (Post Hoc)**	**Sample Size (A Priori)**	**Power (Post Hoc)**
0.05	93	>0.999	225	0.49
0.08	37	>0.999	89	0.967
0.1	24	>0.999	58	>0.999
	N = 1059 df = 281		N = 135 df = 57	

7. Discussion

Whether it is for active or sustainable mobility, walking and cycling represent two very important means of transportation. It is essential that we better understand the drives for selecting such alternatives in everyday life. In this study, we followed the implementation of a number of pedestrian crossings along the bike lane of a shared space infrastructure for pedestrians and cyclists. We then conducted a quantitative analysis of exploratory nature to unravel the behavior and perceptions of users, taking into account their overall experience and perceptions. Previous interactions with other road users (e.g., near misses) are of essential importance in the formation of perceptions and attitudes, and these interactions can also affect the overall opinion about the infrastructure, as has been recognized by previous studies [15,32]. Although the pedestrian crossings do not physically separate the two groups of users, they may create a sense of "order" in the interactions between users. In the case of pedestrians, the pedestrian crossings were not perceived for facilitating only interactions that were related to the behavior of cyclists, but they were also related to the perceived quality of the infrastructure. That is, although shared spaces may be more optimal solutions with respect to saving space, they may not be as well-received by users who may prefer some form of structure in the interactions. This is further validated in the pedestrians' model, where there was a relationship between the positive impact in the interactions from the presence of the pedestrian crossings and the preference for the implementation of further interventions, comprising both soft and hard interventions. The latter components were also negatively related to the overall perceived quality, which is a factor that is also related to the perception of the pedestrian crossings. A very interesting finding was that for the pedestrians, a preference towards the implementation of hard interventions was positively related to higher levels of stated aggressive behavior. It should be noted that previous studies identify a clear preference among pedestrians for a clear indication of the cycling lane [12,13]; meanwhile, the preference among cyclists opinions are split; some studies identify that cyclists also prefer a clear indication of the cycling lane [23,33], while another study has identified that cyclists prefer mixed traffic conditions [13]. Moreover, perceptions about the contribution of the pedestrian crossings in facilitating interactions was also significant, along with the perceived behavior and perceptions towards sharing the infrastructure. For cyclists, the relationship between the perception of aggressive behavior about pedestrian crossings (and hence the current state of things) is indirect, as the latter item was associated with the implementation of hard interventions. For both pedestrians and cyclists, the perception that the pedestrian crossings could facilitate interactions also influences the sense of safety. We can hence observe a pattern that is similar to the existing situation in the interactions between pedestrians and motorized traffic; the pedestrian crossings provide some sort of structure in the interactions, determining priorities and potentially raising the perceived safety and overall perceived reliability of the system. Although the implementation of pedestrian crossings along a bicycle lane may have less defined rules in practice, it also denotes some sort of order in the execution of interactions. Of course, this is most likely the case for the users who agree with this specific measure. Unravelling our conceptual framework backwards, the preference for using the pedestrian crossings or perceiving additional safety by their presence is ultimately related to the initial perception about shared spaces. Regardless of if they are users who perceive the pedestrian crossings as useful and prefer to use them or users who simply exhibit aggressive behavior in interactions that take place in the bicycle lane, the common element is the distinct separation and definition of rules in the interactions. This is an expecting finding, as the difference in how a group of users perceives the other was evident in the inferential statistics analysis. The competitiveness of how the groups perceive each other was reflected in them having similar variables regarding the attitudes towards the pedestrian crossings and their extensions in defining rules for interactions, which are eventually linked to negative behavior and the preference for interventions that would separate the users.

Of course, while interpreting our results, one needs to consider that all responses were collected via an online survey; no field measurements were performed to confirm the validity of the trends found in our data. This has two main potential negative extensions that could induce bias to our results: (a) our findings only represent the views of those familiar with online technologies and which could access the survey; and (b) there is no validation regarding the actual situation. On top of these issues, one must consider that our sample mostly consisted of university students; this was mainly due to the channels that we used for the circulation of the survey, which was web-based and was not performed in person due to the COVID restrictions at the time. Another major issue that potentially affected our capability in observing significant results was the low sample size for cyclists, which can be attributed to the same reasons. Although it is very likely that the proportion between pedestrians and cyclists would be comparable in real-life observations at the shared infrastructure, additional data are still required to deduce more robust conclusions with respect to cyclists. Hence, subjectivity is an issue here, which was made obvious when the perceptions of the two groups of users were compared for similar matters and when significant differences were found. Moreover, our results are potentially more representative for specific groups of pedestrians and cyclists rather than the total population of these users. Potential extensions of the current research could focus on collecting the same data from a broader sample via an in-person data collection rather than online data collection. Moreover, more observations from cyclists are required. Additionally, field observations at crossings and bike lanes in general locations could provide very useful insights with respect to the existing situation and interactions between users. It must be mentioned that the initial objective of the current research study was to collect field observations; however, due to circumstances related to the COVID-19 pandemic, the original research direction was changed. However, it must be highlighted that when investigating factors behind use or intention to use, survey data are more crucial in order to understand the underlying factors. Field observations, on the other hand, can have a supplementary role in providing insights with respect to the discrepancies between how one perceives themselves and the actual situation.

Nevertheless, the patterns observed in our conceptual framework, which was applied to a great extent in both of our samples, suggest that some level of segregation is desirable. Even though our sample considered the physical separation as important, such an intervention could reduce the flexibility and comfort for all users. Hence, measures such as different coloring or surface material and additional vertical signs could enhance the sense of separation and improve user interactions. Given the preferences towards some sort of separation, it is very likely that completely unmarked shared spaces could be confusing for users and could lead to considerably lower cycling speeds. This seems to be the case at least in cities, where cycling and space sharing experience is limited, as such an experience is essential for the harmonious co-existence of users and can highly affect users' perceptions [22]. At the same time, cycling lanes must be sufficiently wide enough to allow for a good level of service for the bicycle flows. Despite the implementation of any potential intervention, a major issue, as derived from our inferential statistics analysis, is based on the beliefs that the two groups of users have for each other, which could suggest a mutual perceived lack of respect. For instance, it is very likely that cyclists do not feel additional safety due to the presence of crossings, as they also believe that pedestrians do not cross only from these areas. On the other hand, pedestrians perceive cyclists as more aggressive compared with how the latter group perceives themselves. Although these issues are overlooked due to the small number of physical conflicts and their low severity, it must be ensured that users understand how to behave when using specific parts of the infrastructure. This issue, combined with the previously mentioned challenges, must be kept in mind both during the development of new infrastructure and the implementation of interventions in existing infrastructure by the respective authorities.

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Appendix A

Table A1. Factor loadings of the pedestrians' sample EFA analysis.

Expected Factor	Derived Factor	Items	Item Code	Factor Loading
Pedestrian and pedestrian crossing	Behavior at pedestrian crossing	Check for oncoming bicycles before crossing	I_1	0.756
		React with anger when cyclist does not give priority	I_2	−0.748
	Attitudes towards using the pedestrian crossing	Choice of pedestrian crossings to cross the bike lane	I_3	0.773
		Increased sense of safety when choosing the pedestrian crossing	I_4	0.74
Perception about cyclists' behavior	Cyclists' behavior	Cyclists reduce their speed at pedestrian crossings	I_5	0.95
		Cyclists give priority at pedestrian crossings	I_6	0.659
		Cyclists are moving within the bike lane boundaries	I_7	0.361
	Cyclists' anger	Cyclists react with anger when pedestrian crosses from a pedestrian crossing	I_8	0.997
		Cyclists react with anger when pedestrian does not cross from a pedestrian crossing	I_9	0.461
Perception about the pedestrian crossing	Positive effect of pedestrian crossing	The pedestrian crossings facilitate interactions	I_{10}	0.783
		The pedestrian crossings provide additional safety	I_{11}	0.72
		The pedestrian crossings facilitate the pedestrians' flows	I_{12}	0.585
		The pedestrian crossings facilitate the cyclists' flows	I_{13}	0.498
	Negative effect of pedestrian crossing	The pedestrian crossings interrupt the cyclists' flows	I_{14}	0.678
		The pedestrian crossings interrupt the pedestrians' flows	I_{15}	0.494
Quality indicators of the shared infrastructure (Overall quality)		Aesthetics/environment	I_{16}	I_{16}
		Comfort	I_{17}	I_{17}
		Safety	I_{18}	I_{18}
		Cleanness	I_{19}	I_{19}
Interventions	Soft interventions	Different material for the pedestrian crossings	I_{20}	0.662
		Additional signs at the pedestrian crossings	I_{21}	0.659
		Additional lighting at the pedestrian crossings	I_{22}	0.649
		Different surface material for the bike lane	I_{23}	0.615
		Different coloring of the bike lane	I_{24}	0.577
	Hard interventions	Different location for the bike lane	I_{25}	0.655
		Physical separation of the bike lane	I_{26}	0.362

Table A2. Factor loadings of the cyclists' sample EFA analysis.

Expected Factor	Derived Factor	Items	Factor Loading
Cyclists and pedestrian crossings		Speed reduction at pedestrian crossings	0.756
		Give priority to pedestrians at pedestrian crossings	0.765
Perception about pedestrians' behavior	Pedestrians' behavior	Pedestrians are respecting the bike lane boundaries	0.86
		Pedestrians are checking for oncoming bicycles when crossing	0.73
		Pedestrians are choosing the pedestrian crossings to cross	0.604
	Pedestrians' anger	Pedestrians are reacting with anger with cyclists do not give them priority	0.581
Perception about the pedestrian crossings	Positive effect of pedestrian crossings	The pedestrian crossings provide additional safety	0.795
		The pedestrian crossings facilitate interactions	0.753
		The pedestrian crossings facilitate the cyclists' flows	0.488 (−0.53 *)
		The pedestrian crossings facilitate the pedestrians' flows	0.455
	Cyclists' flow *	The pedestrian crossings interrupt the cyclists' flows	0.7 *
Quality indicators of the shared infrastructure (overall quality)		Aesthetics/environment	0.803
		Comfort	0.603
		Safety	0.597
		Cleanness	0.713
Interventions	Soft interventions	Additional signs at the pedestrian crossings	0.761
		Additional lighting at the pedestrian crossings	0.545
		Different material for the pedestrian crossings	0.446
		Different coloring of the bike lane	0.328
	Hard interventions	Different location for the bike lane	0.62
		Physical separation of the bike lane	0.542
		Different surface material for the bike lane	0.417

* Loadings associated to the Cyclists' flow factor.

Table A3. Measurement model results of pedestrians' model.

Paths			Estimate	z-Value	P (>∣z∣)
Perceived cyclists' (positive) behavior	←	I_7	0.43	12.75	0.000
Perceived cyclists' (positive) behavior	←	I_5	0.90	17.69	0.000
Perceived cyclists' (positive) behavior	←	I_6	0.93	17.65	0.000
Overall quality	←	I_{17}	0.81	27.17	0.000
Overall quality	←	I_{18}	0.60	24.03	0.000
Overall quality	←	I_{16}	0.96	28.27	0.000
Overall quality	←	I_{19}	0.68	25.25	0.000
Soft interventions	←	I_{22}	0.62	21.48	0.000
Soft interventions	←	I_{23}	0.65	21.10	0.000
Soft interventions	←	I_{20}	0.73	22.20	0.000
Soft interventions	←	I_{21}	0.65	21.84	0.000
Soft interventions	←	I_{24}	0.57	19.81	0.000
Hard interventions	←	I_{25}	0.17	4.23	0.000
Hard interventions	←	I_{26}	0.25	4.46	0.000
Positive effect of pedestrian crossings	←	I_{11}	0.76	23.20	0.000
Positive effect of pedestrian crossings	←	I_{10}	0.75	22.87	0.000
Positive effect of pedestrian crossings	←	I_{13}	0.49	18.11	0.000
Positive effect of pedestrian crossings	←	I_{12}	0.58	19.87	0.000
Pedestrians' (negative) behavior	←	I_1	1.13	13.73	0.000
Pedestrians' (negative) behavior	←	I_2	−0.71	−15.52	0.000
Attitudes towards using the pedestrian crossings	←	I_3	0.77	17.09	0.000
Attitudes towards using the pedestrian crossings	←	I_4	1.19	15.54	0.000

Table A4. Goodness-of-fit indices.

Measure	Value	
	Pedestrians' Model	**Cyclists' Model**
Absolute fit		
RMSEA	0.059	0.020
SRMR	0.064	0.077
GFI	0.98	0.979
Incremental fit		
AGFI	0.976	0.971
CFI	0.850	0.966
TLI	0.828	0.961

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