# Pedestrian Behavior in Virtual Reality: Effects of Gamification and Distraction

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**Abstract**

As a tool for pedestrian research, virtual reality is appreciated for its safety, flexibility, and high experimental control. At the same time, differences between simulator studies and real-world traffic may affect behavioral outcomes. While continuous technological advancements counteract shortcomings such as a limited field of view, effects of motivation and attentional focus tend to be neglected. This appears inappropriate, as recurrent street crossing and similarly repetitive tasks can impair motivation, while distractors common to naturalistic settings are typically absent in scripted scenarios.

Focusing on the experimental context, the present study aims to contribute to the methodological evaluation of pedestrian simulators. Thirty-six participants performed repeated virtual street crossings displayed via a head-mounted display. Motivational incentives arising from the use of game elements and moderate cognitive load induced by a secondary task were investigated with regard to crossing behavior, play experience, and the feeling of presence. Gamification thereby affected walking speeds, the size of selected gaps, and temporal safety margins. A moderately challenging secondary task, in contrast, significantly reduced both play experience and the feeling of presence, but did not influence crossing behavior. As expected, game elements enhanced play experience, whereas reports of presence did not change significantly. Although the mechanisms employed arguably differ from naturalistic sources of motivation and distraction, our findings underline that individual incentives and attentional resources are relevant to future experimental designs. The disagreement of subjective and objective responses further implies that changes in presence do not equate an adjustment of behavioral reactions.

**Keywords**

Virtual Reality; Pedestrian; Distraction; Gamification

## 1. Introduction

Vulnerable road users, who lack physical protection in case of an accident, constitute more than half of worldwide traffic fatalities [1]. Despite an overall decline in the number of casualties, the subgroup of pedestrians represent 21% of traffic deaths in the European Union [2]. For low-income countries, this proportion is notably higher [3]. Besides the lack of physical protection, causes lie in vehicle and infrastructure design that prioritizes motorized traffic [1]. Consequently, the World Health Organization demands rapid improvements, supporting traffic safety for those who are particularly endangered [1].

Prior to time-consuming and expensive field studies, possible safety measures can be evaluated by using virtual reality (VR) to display traffic scenarios from a pedestrian's perspective. As technological advancements render suitable hardware and software solutions increasingly accessible, such setups, commonly referred to as pedestrian simulators, gain popularity. A number of systems have been proposed, for instance to investigate navigational aids [4], warning devices [5], and concepts related to progressive vehicle automation [6]. Just like driving simulators [7], pedestrian simulators are appreciated for their safety, flexibility, and high experimental control. However, various factors can influence the measures of interest and dissimilarities in regard to naturalistic traffic may not only arise from a mismatch of sensory cues, but also from particularities in scenario design. Restrictions such as a low resolution, limited tracking range, and a small field of view preventing peripheral vision are thereby continuously counteracted by technological advancements, which are accelerated by the short development cycles of VR goggles and the high competition among commercial manufacturers. Scenario design, in contrast, has not been a particular focus of previous research.

Based on the complexity inherent to naturalistic traffic, considering attentional resources and motivational context seems relevant to the meaningful interpretation of pedestrian behavior. Existing validation attempts [8–10], however, mainly consist in transferring a relatively artificial task, such as repeatedly crossing the same street, from a virtual to a physical environment. Although certainly valuable to establish VR as a replacement for cumbersome physical laboratories, such comparisons account for effects of neither attentional focus nor motivational state. Utilizing VR to evaluate vehicle sounds, [10] noted that detection times increased when a car's arrival time was longer. The authors explain this finding by decreasing attentional resources during the vehicle's approach, questioning designs that display the cues to detect right from the beginning or at constant time intervals. The high predictability of experimental scenarios is supported by the short durations of common tasks such as street crossing, which render required actions repetitive and arguably less realistic.

Due to its safety relevance and relatively limited space requirements, street crossing is one of the most common scenarios in pedestrian simulators. The decision to cross can thereby be seen as a trade-off between saving time and minimizing the risk of injuries [11]. While the extent of time pressure depends on the context, it appears unnatural to traverse a street just for the sake of crossing. Instead, in a more realistic setting, actors move to reach a certain destination. Hence, perceived meaningfulness might suffer in simulator studies, resulting in reduced motivation, boredom and fatigue.

One approach to raise motivation consists in adding game elements to non-game contexts, which is commonly referred to as gamification [12]. Albeit dependent on characteristics of both user and content [13], gamification has shown positive effects, among others by stimulating perceived competence [12]. Considering the bandwidth of successful applications, similar mechanisms are likely to pertain to pedestrian simulation. In fact, time pressure, which is related to elements such as counters or temporal restrictions, was already shown to alter pedestrian behavior: The sound of a ticking clock compromised crossing safety in both children and adults [14] and children engaged in riskier behavior when the instructions stressed the need to act quickly [15].

A further difference in comparison to naturalistic traffic concerns distraction. [16] found approximately a third of pedestrians to be distracted while crossing, compromising safety-related gaze behavior. In laboratory settings, a secondary task was shown to lower walking speed, reduce the accuracy of the walking trajectory, and impair performance in a detection task [17]. The extent of detriments depended on the task to perform, with gaming impacting detection times more strongly than texting or watching a video [17]. In a dual-task condition, [18] found reading to result in the highest subjective workload and the lowest situational awareness. The detection of roadside events was delayed for both reading and texting in comparison to a picture-dragging task. Furthermore, the three tasks were related to distinct gaze patterns. For children aged 10 to 11, a cell phone conversation resulted in longer waiting times, delayed crossing, and a higher risk of collisions [19]. Delayed crossing was also reported for adults both when texting and when engaging in a phone conversation [20,21]. Considering the high number of potential distractors in naturalistic traffic, performance detriments due to secondary tasks indicate that the restricted attentional focus in many controlled experiments might be too artificial to generalize findings.

In the present study, we examined the influence of factors that distinguish widespread experimental designs from real-world traffic. Motivational incentives and cognitive load were selected to represent two relevant aspects. Regarding the former, game elements were employed to mimic time pressure and personal objectives common to naturalistic crossings. In contrast to previous studies focusing on mobile devices [17,18], cognitive load was induced by a secondary task which required neither motoric inputs nor the processing of visual cues. This way, we focused on cognitive aspects of distraction, including the seemingly less intrusive but common interference due to headphones [16]. No direct comparison to real world was conducted for methodological reasons, since cognitive load and motivation are hard to quantify in naturalistic traffic. Instead, we considered changes in pedestrian behavior within a laboratory setting as a sign for the importance of the investigated factors, highlighting the need to account for them in future research.

## 2. Methodology

### 2.1 Experimental Design

A two-factorial mixed design was employed. To avoid carry-over effects, the use of game elements was varied between groups. Cognitive load, in contrast, whose effects were expected to primarily depend on individual capacities and thus to be unbiased by a direct comparison between the two conditions, was varied within participants. All subjects were instructed to cross a one-way street safely, but as fast as possible. For half of them, the virtual environment was enriched with game elements and the task was described as "game" to induce a game-related mindset. By crossing the street, participants in this group collected golden coins, which repeatedly appeared on the opposite walkway. Each time a coin was collected, they were rewarded 15 virtual points, whereas they would lose 40 points in case of a virtual collision. Furthermore, one point was subtracted every five seconds to induce a sense of time pressure. The rules about gaining and losing points were communicated in advance. Notably, points were purely virtual and not related to any physical or monetary reward. Participants could see their current score, which was highlighted at every change, and a timer in the bottom right corner of their visual field. Collecting a coin or being hit was accompanied by typical game sounds. In the control group, in contrast, the study design yielded no game elements and no incentives beyond the experimenter's instructions.

While the boundary between games and gamification is sometimes unclear, common definitions stress the developer's perspective [22]. In the present case, game elements were employed to enrich an existing street crossing task. This was considered an act of gamification, although, given the use of the term "game" in the instructions, members of the experimental group may have judged their experience as a game rather than merely gamified. Such an impression, however, can be assumed at least equally influential in regard to their motivational state. Furthermore, stressing the target of safe crossings in both groups, it is unlikely to cause a qualitatively different effect than the game-like context suggested by other game elements.

To manipulate cognitive load, each participant experienced one block of crossings while performing a secondary task. An auditory n-back [23] was selected to avoid interference with the primarily visual perception of cars. Participants thereby listened to recorded sequences of ten numbers each, verbally repeating the element that was presented "n" places prior to the latest one. As a measure of working memory, the amount of necessary resources depends on the size of "n": The more elements one has to memorize, the higher the cognitive load. In the present study, a 1-back task was employed, requiring participants to repeat each element after the following number. For this task, informal feedback from pre-tests indicated cognitive load to be elevated but moderate. Hence, this activity was deemed comparable to a phone call or a captivating train of thought, presumably reflecting cognitive load in real-world scenarios. Furthermore, while visual-manual tasks may impair traffic safety more strongly, we do not expect pedestrians to routinely perform them when crossing a non-signalized street. Instead, highly intrusive tasks such as gaming and texting may be interrupted, whereas cognitive distraction is likely to influence pedestrians more permanently.

### 2.2 Materials and Participant Sample

Thirty-six subjects (25.0 ± 3.43 years of age, 14 females) were recruited via personal contacts and flyers on the university campus. Males and females were equally distributed between the two experimental groups. All cars moved at a constant speed of 30 km/h, with temporal gaps between them varying in steps of 0.25 to 0.50 s. The participant's task consisted in selecting a gap that was large enough to safely reach the opposite side of the street. As gaps between cars increased over time, selecting larger gaps resulted in longer waiting times.

The virtual environment, built in Unity 2018.2, comprised a single lane of 3.5 m width. Surrounding buildings were modeled after the urban center in Munich, Germany (Figure 1). The scenery was displayed via an HTC Vive Pro headset, offering a nominal field of view of 110 degrees and stereoscopic vision at a resolution of 1.440 x 1.600 pixels per eye. The interpupillary distance was measured and adjusted individually. Headphones provided stereo sound of the vehicle engines and additional auditory cues depending on the experimental condition. Restricted by the tracking range and the physical borders of the room, participants could walk freely within an area of approximately 4.5 m x 4.5 m.


**Figure 1: Sample of the virtual environment without (left) and with (right) game elements.**

After receiving information about the experimental procedure and providing informed consent, participants read out a series of digits displayed at a distance of 1.5 m within the virtual environment to ensure sufficient visual acuity and an appropriate fit of the headset. To get acquainted with the setup, they performed each two crossings without and two crossings with approaching vehicles. Afterwards, they completed two experimental blocks, each comprising 16 trials, and subsequent questionnaires on presence and play experience, complemented by additional demographic questions after the second part. The 1-back task was explained and practiced immediately before the respective block, whose order was counterbalanced across participants. The study was approved by the local ethics committee.

### 2.3 Dependent Measures

To account for differences in starting positions, measures of crossing behavior only referred to the time period during which the participant was located in the middle part of the lane which corresponded to the vehicle width. For each crossing, several parameters were analyzed: *Maximum and average walking speed* were derived from the headset's movements perpendicular to the street. Maximum speed represented the highest absolute derivative of the headset's position, whereas average speed was calculated by dividing the time participants spent on the street by the distance covered. Since only the middle part of the lane was considered, acceleration and deceleration were not taken into account. *Gap size* corresponded to the temporal gap between the two cars between which the pedestrian decided to cross. It was calculated under consideration of the vehicles' spatial dimensions and velocities. *Post encroachment time* (PET) was defined as the time between the moment when the pedestrian left the middle part of the street and the moment the vehicle passed his or her crossing line. Negative PETs indicate a virtual collision.

To collect data on the subjective properties of presence and play experience, questionnaires were employed. The Play Experience Scale (PES) [24] reflects self-reports of intrinsic in contrast to extrinsic motivation, an attentional focus on the task at hand, and the absence of work-related thoughts and feelings. It consists of four subscales labelled *Autotelic experience/Focus*, *Freedom*, *Absence of extrinsic motivation*, and *Direct play assessment*. Its 16 items are rated on a 6-point Likert scale. The PES was chosen because of its focus on motivational aspects and its suitability for an unspecific game context. In contrast to the original scale, the word "game" was replaced by "simulation" in both groups. The Presence Questionnaire (PQ) was included to assess the feeling of presence, which is understood as the subjective impression to be part of a virtual or remote environment and frequently linked to the realism of a simulation [25]. For the scope of this study, we used the first 22 items of a revised version [26], comprising the subscales *Realism*, *Possibility to act*, *Quality of interface*, *Possibility to examine*, *Self-evaluation of performance*, and *Sounds*, which were rated on a 7-point Likert scale.

## 3. Analysis and Results

### 3.1 Crossing Behavior

Crossing behavior was analyzed by means of the statistical software R [27] and the package nlme [28]. Figure 2 displays descriptive results for the four parameters used to quantify walking behavior collapsed across all participants. The addition of game elements seemed to affect all measures considered, resulting in higher walking speeds, smaller gaps to be accepted, and smaller PETs. In particular with regard to the latter two parameters, variance decreased. The effect of cognitive load, in contrast, seemed negligible.

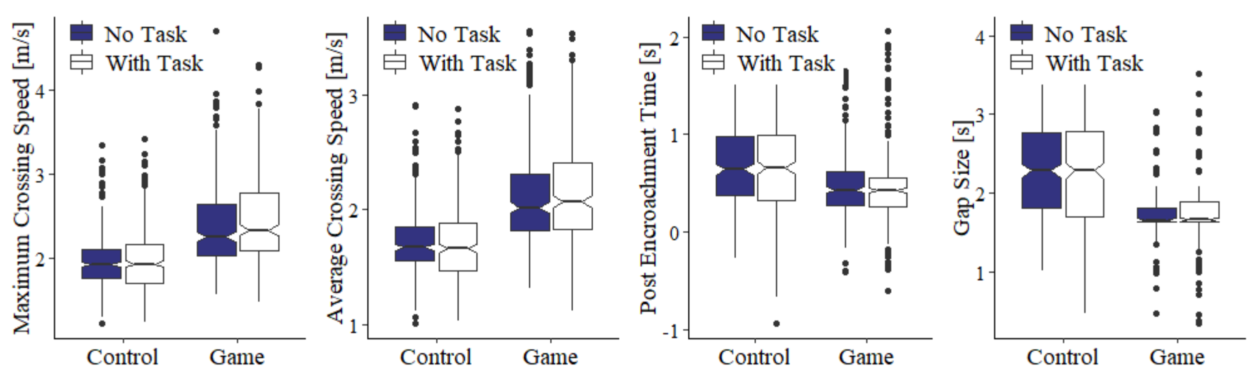


**Figure 2: Crossing behavior according to the experimental condition. Notches correspond to the 95% confidence interval of the median.**

Differences in crossing speeds, the size of selected gaps, and PETs were examined by mixed linear models, accounting for random intercepts and slopes as well as for interaction terms [29]. The underlying model is depicted by equation (1), with y representing the respective crossing parameter. The asterisk implies that not only the main effects of game elements and cognitive load, but also their interaction was analyzed. The term (Cognitive Load)|Participant specifies that intercepts and regression coefficients of cognitive load were allowed to vary between participants. This reflects the expectation that not only absolute values, but also the sensitivity to cognitive load differs between individuals.

$$y \sim Game\ Elements * Cognitive\ Load + (Cognitive\ Load)|Participant \qquad (1)$$

In all cases, considering both random intercepts and random slopes for cognitive load significantly improved the model fit as indicated by lower AIC and BIC and a higher log-likelihood ($p < .001$). Based on graphical inspection of the residuals, no heteroscedasticity was evident for any of the models. Q-Q plots demonstrated a long tailed deviation from the normal distribution. While estimated regression coefficients can be expected to be unbiased, care should thus be taken when interpreting confidence intervals and p-values.

Table 1 summarizes the results of the regression analysis, which were in line with the descriptive statistics. While game elements affected all measures of crossing behavior, the opposite was true for cognitive load. Furthermore, none of the interaction terms were significant, indicating effects of game elements to be independent of the moderate cognitive load caused by the 1-back task. The addition of game-like motivational incentives caused participants to accept smaller gaps. Despite higher walking speed, PETs were thereby reduced, indicating smaller temporal safety margins. As evident from Figure 2, these differences are mainly attributable to reduced variability, notably limiting the number of large gaps and PETs. Variance in walking speeds, in contrast, tended to be lower in the control group. Since PETs below 0 indicate a virtual collision, it is furthermore noteworthy that the latter occurred in all experimental conditions. Due to their overall small number, however, no inferential analysis was performed with respect to their frequency.

**Table 1: Inferential statistics on crossing behavior.**

| | | Estimated coefficient | 95% Confidence interval | | *SE* | *df* | *t* | *p* |
|---|---|---|---|---|---|---|---|---|
| Maximum Walking Speed | | | | | | | | |
| | Game Elements | 0.437 | [ 0.172; | 0.701] | 0.092 | 34 | 3.352 | .002 |
| | Cognitive Load | 0.013 | [-0.060; | 0.085] | 0.130 | 1072 | 0.339 | .734 |
| | Interaction Term | 0.056 | [-0.047; | 0.158] | 0.052 | 1072 | 1.061 | .288 |
| Average Walking Speed | | | | | | | | |
| | Game Elements | 0.405 | [ 0.165; | 0.646] | 0.119 | 34 | 3.415 | < .001 |
| | Cognitive Load | 0.003 | [-0.067; | 0.073] | 0.036 | 1072 | 0.091 | .927 |
| | Interaction Term | 0.048 | [-0.051; | 0.146] | 0.050 | 1072 | 0.945 | .345 |
| Post Encroachment Time | | | | | | | | |
| | Game Elements | -0.232 | [-0.454; | -0.011] | 0.109 | 34 | -2.128 | .041 |
| | Cognitive Load | -0.036 | [-0.151; | 0.079] | 0.059 | 1072 | -0.613 | .540 |
| | Interaction Term | 0.036 | [-0.126; | 0.198] | 0.083 | 1072 | 0.438 | .662 |
| Gap Size | | | | | | | | |
| | Game Elements | -0.571 | [-0.905; | -0.237] | 0.165 | 34 | -3.464 | .002 |
| | Cognitive Load | -0.045 | [-0.144; | 0.055] | 0.051 | 1072 | -0.881 | .379 |
| | Interaction Term | 0.062 | [-0.078; | 0.203] | 0.071 | 1072 | 0.871 | .384 |

### 3.2 Subjective Data

Questionnaires were analyzed by means of mixed ANOVAs using the software JASP [30]. Inversed items were recoded and single missing values were replaced by the mean of the respective subscale. Due to technical problems, questionnaire data were missing for a total of five questionnaires (3 x PES, 2 x PQ) from four participants. Data from these participants were excluded from the respective analysis but contributed to the results regarding the second questionnaire. In line with previous research, item scores were averaged for the PES, whereas the sum of all items was calculated for the PQ [31].

Figure 3 displays descriptive results of the PES. Since no specific hypotheses existed in regard to the subscales and in line with previous research [31], inferential statistics were only performed on the total score, revealing a significant effect of both game elements ($F(1,32) = 15.75$, $p < .001$, $\omega^2 = 0.303$) and cognitive load ($F(1,32) = 16.28$, $p < .001$, $\omega^2 = 0.062$). As expected, game elements increased play experience. A moderately challenging secondary task, in contrast, lowered it, albeit to a lesser extent. Although mean values indicated the effect of cognitive load to be larger in the gamified condition, the interaction term was insignificant ($F(1,32) = 1.599$, $p = .215$). Descriptively, the same pattern as for the total score emerged for all subscales, even if effects seemed most pronounced for *Direct play assessment* and *Autotelic experience/Focus*.

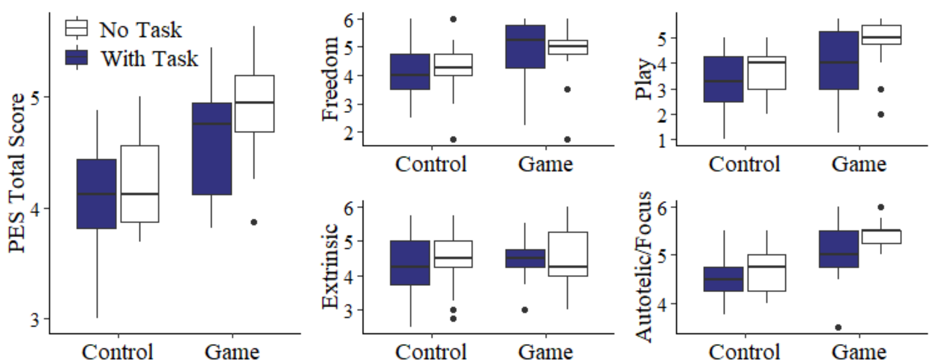


**Figure 3: Mean scores for the PES and its subscales according to the experimental condition.**

Figure 4 displays the results of the PQ. Again, only the total score was submitted to inferential analysis, while descriptive information on the subscales is provided for illustration. Based on a two-factorial mixed ANOVA, cognitive load resulted in a lower feeling of presence ($F(1,32) = 4.569$, $p = .040$, $\omega^2 = 0.011$), whereas effects of game elements failed to reach statistical significance ($F(1,32) = 3.913$, $p = .057$). Again, the interaction term was insignificant ($F(1,32) = 0.681$, $p = .415$) and descriptive results for most subscales indicated the same pattern as for the total score. Exceptions concerned the perceived *Quality of interface* and the *Self-evaluation of performance*, for which a secondary task reduced scores in the gamified group, whereas values increased in the control condition. The opposite was true in regard to the *Sounds* scale.

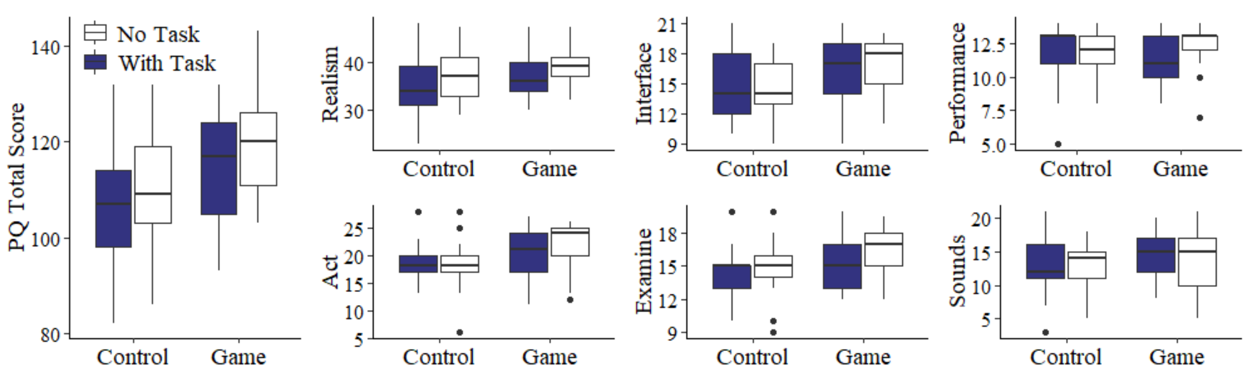


**Figure 4: Sum scores for the PQ and its subscales according to the experimental condition.**

## 4. Discussion

### 4.1 Summary

For street crossing in a virtual environment, the present study investigated effects of motivational incentives and a secondary task competing for cognitive resources. Game elements increased both maximum and average walking speeds, resulted in smaller gaps to be accepted, and shortened post encroachment times. As expected, they enhanced play experience, whereas the influence on presence was not significant. A moderately challenging secondary task, in contrast, significantly reduced both play experience and the feeling of presence, but did not affect crossing behavior. No interaction between game elements and cognitive load was observed.

### 4.2 Gamification

The addition of game elements changed observable behavior in a common street crossing scenario. In comparison to naturalistic traffic, some of the accepted gaps thereby seem unrealistically small. Based on camera observations, [11] predict a median accepted gap of at least three seconds depending on the traffic site and the pedestrian's starting position. Regarding walking speed, the authors assume 1.5 m/s to be comfortable, while they expect velocities of about 3 m/s for evasive actions. Referring to the time between crossing initiation and the vehicle passing the pedestrian, [32] report a median of 3.29 s and a minimum of 0.50 s. In particular in the gamified group, our results imply notably smaller gaps and walking speeds above the "comfortable" threshold (Figure 2). However, [11] also observed the size of gaps to decline for narrower intersections. Since all sites in their study comprised several lanes, cumulatively equaling a width of at least 20 meters and thus over five times the width in the current scenario, comparability may be limited. Additionally, in naturalistic traffic, careful people are likely to wait for larger gaps or even an empty road, whereas in the present study, there was no reason to expect such a decrease in traffic density.

When focusing on time pressure as a frequent component of gamification, the results confirm findings of riskier crossing behavior [14,15], with adjustments in walking speed resulting from evasive actions [33]. However, time pressure is not the only mechanism that can be expected to affect behavior in the present study. [12] name feelings of efficiency and success as a central motivator of human behavior. In the gamified group, the sense of progress was likely fostered by scores providing continuous feedback [12] and by perceivable changes in the virtual scene accompanying the user's actions (such as sounds and the appearance of virtual coins). Furthermore, [12] found progress indicators such as leaderboards and badges to promote the perceived meaningfulness of the task. Unlike time pressure, such positive feelings are likely to explain the effects on subjective play experience, resulting in values comparable to actual games [24].

In comparison to the control group, on average smaller gap sizes in the gamified condition mainly stem from an underrepresentation of large gaps. The restricted variance might indicate changes in decision strategies. Instead of waiting for a more comfortable crossing opportunity, participants accepted the closest possible gap. Although gap sizes on average decreased by more than half a second, PETs in the gamified group were however only reduced by approximately 0.2 s. Accordingly, participants compensated for their choice by more accurate timing and higher walking speeds, attenuating effects on temporal safety margins. Such behavior can be understood as a sign of motivation to perform well rather than negligence.

Notably, the scoring system was designed to reward safe rather than fast crossings, since one would lose fewer points even for a three-minute waiting time than in case of colliding. It is possible that, given the rare event of a collision in comparison to the successive loss of one point every five seconds, time constraints were simply more obvious. On the other hand, although no data was collected on individual goals and the understanding of the reward system, informal observations and comments support stronger personal engagement and more positive emotions in the gamified group. Future research might clarify the mechanisms that mediate between the perception of game elements and changes in crossing behavior. Special attention should thereby be paid to techniques that were not included in the present study, such as background stories to increase the perceived meaningfulness of the task [12]. Since certain measures stimulate specific sources of motivation [12], cover stories stressing the importance of safe crossing and changes in the reward system might result in different behavior.

Overall, values in the control group appear closer to real-world observations [11]. While the selected game mechanisms thus seem suitable to induce motivational incentives, they do not appear to foster predictive validity with regard to naturalistic traffic. In fact, behavioral changes are likely not limited to the purposeful selection of game elements, but can also occur if a game-like feeling is unintended. Relatively high PES scores in the control group imply some degree of play experience even in the absence of additional game elements, which is possibly supported by a common association between VR and gaming experience. In the present study, game-related emotions and thoughts might have elicited riskier decisions, triggering for example normative beliefs that - despite the absence of a comparison to others - stressed competition and the goal of "winning". Adding to obvious differences regarding the consequences of collisions, such a perception might cause riskier decisions, limiting the predictive value of experimental data. The degree to which the simulation is perceived as a game should thus be seen as a potential confounder in future studies.

### 4.3 Cognitive Load

Although cognitive load resulted in lower ratings of both presence and play experience, crossing behavior was unaffected. Considering the small regression coefficients, the lack of significance is unlikely to reflect a statistical artifact. Based on existing literature, distraction was expected to delay crossing initiation [20,21]. In the current design, this would either cause later and thus larger gaps to be accepted, or lead to smaller PETs, possibly attenuated by higher walking speeds. A lack of significant changes in either of these measures, in contrast, implies that participants were able to fully compensate for the moderate, non-visual distraction.

Cognitive load can evoke different types of strategic adjustments [34]. Given the relatively simple street crossing task, performance might not have suffered from a moderate decline in attentional resources. The complexity of naturalistic traffic, in contrast, likely complicates an adequate strategy to balance simultaneous tasks. Furthermore, while phone calls, music, or a personal train of thought may have an emotional character, no such qualities were incorporated in the present design. Additionally, reactions among participants might differ, with some acting more cautiously and others demonstrating riskier behavior. Since only overall tendencies were examined, no final conclusion can be drawn on this issue. However, contrasting adaptations should result in higher variance, which was supported by the data only to a limited extent. Hence, although different strategies might exist, behavioral changes in general appear to be small.

In particular for short time periods, humans may offset higher demands at the cost of subjective comfort [34]. Although not evident in crossing behavior, questionnaires indicated that the secondary task altered personal involvement. Play experience decreased for higher cognitive load, with lower ratings in particular pertaining to items that contrasted play and work. The secondary task thus seemed to increase demands to a level that was perceived as unpleasant or exhausting, thereby interfering with the otherwise playful experience of virtual street crossing. According to PQ scores, participants felt less connected to the virtual environment when performing the 1-back, possibly due to the fact that it was unrelated to the urban traffic scenario. The strongest decline in ratings thereby concerned the items "How natural did your interactions with the environment seem?" and "How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?". While the former item implies that the selected task seemed artificial, the latter once more indicates perceived effort. Although effects were relatively small, the observed differences suggest that the chosen manipulation was effective in raising cognitive load, which, however, did not alter crossing behavior.

Based on previously observed performance decrements [17,18], one might question the difficulty of the task. Not only the relatively young age, but also the predominantly academic background of the participant sample suggests above average mental capacities. Since our aim was to mimic a realistic extent of distraction and not to determine the threshold above which performance declines, the chosen manipulation was still deemed appropriate. In line with the questionnaires, participants repeatedly stated that they perceived the secondary task as demanding. Nonetheless, n-back performance was not analyzed and cognitive load was not measured directly. The assumption of appropriate effort thus relies on informal observations, and results cannot be generalized to other populations or more demanding activities.

Concerning crossing parameters, results indicate a limited impact of mild cognitive engagement that withdraws attentional resources. Discrepancies in comparison to previous studies can thereby stem from both the kind or difficulty of the secondary task [17,18] and the sensitivity of dependent measures. Future studies should examine effects of emotional valence as well as the interplay of cognitive load and the need for sudden behavioral adjustments, which presumably require more mental resources.

### 4.4 Limitations

In the present study, we aimed to shed light on the influence of motivational incentives and cognitive distraction in virtual street crossing. Interest in this question was partially motivated by a perceived mismatch between the demands in simulator studies and in naturalistic traffic. However, due to methodological constraints, no direct comparison to crossing in a non-experimental setting was possible. While there is evidence of distracted crossing

[16] and unequal motivational incentives seem at least plausible, we cannot quantify to what extent the experimental manipulation reflected real-world circumstances. Nonetheless, our results should sensitize researchers to evaluate differences between the experimental setting and everyday behavior beyond the fidelity of sensory cues.

The scope of the study was limited with regard to both the scenario and the participant sample. Since street crossing belongs to the most common tasks and many studies rely on student samples, limitations seem reasonable from a methodological perspective. However, considering for example the influence of personal characteristics on effects of gamification [13], one should be cautious to overgeneralize the findings. In particular concerning performance decrements due to distraction, additional information is needed in regard to the interaction of task complexity and individual skills and personality.

A final methodological concern refers to the creation of virtual traffic. While gaps were designed to increase over time, it appeared unnatural to make participants wait between disjointed sequences of cars. Continuous traffic also seemed advantageous in terms of immersion. This required large gaps to be replaced by smaller ones at the moment of crossing, and thus cars to virtually "jump" while participants turned their back at the street. Pre-tests and comments during debriefing indicated that, although they occasionally noticed increases in traffic density, participants did not observe unnatural movements. However, the mechanism by which gaps filled was affected by the update frequency, leading to some variance in the size of the first gaps to appear after crossing. This imprecision was tolerated since participants were not expected to accept these gaps. One has yet to acknowledge that in particular the smallest gaps were not necessarily identical for all crossings, although no systematic bias is assumed concerning the comparison of experimental conditions.

## 5. Conclusions

Despite the popularity of pedestrian simulators, little consideration is given to the impact of scenario design. Focusing on two potential confounders, our objective was to examine the extent to which motivation and moderate distraction affected virtual street crossing. The results demonstrate that at least personal incentives are of high relevance and future research should identify mechanisms that support the similarity to real-world traffic.

Strikingly, changes in presence ratings did not seem to correspond to adjustments in observable behavior. Construed as a measure of a virtual environment's "effectiveness" [25], presence is often assessed in pedestrian simulation [8]. Implicitly, higher presence ratings are thereby seen as a sign of the simulator's suitability for evaluating a particular research question regarding human behavior under certain circumstances. The missing link between presence ratings and observable actions challenges this assumption. A similar mismatch was reported by [35], who found divergent patterns for presence ratings and gaze behavior. [31] noted comparable PQ ratings for a physical environment and its virtual replica. In fact, although differences were statistically insignificant, descriptive values in the present study indicated higher presence in the gamified group. Considering the reduced similarity of crossing parameters to those in naturalistic traffic [11], it is important to acknowledge that the sense of being and acting within a virtual environment does not imply the equality of actions to those performed in a visually similar physical setting. Since a large rotating coin and a score counting successful crossings arguably are no part of a typical traffic scene, higher ratings in the gamified group further question the association between presence and what is commonly understood as realism.

Accounting for differences between simulator studies and naturalistic traffic, researchers should evaluate the plausibility of scenarios [10]. The present study constitutes a first step towards examining the factors that distinguish experimental designs from real-world situations. While the manipulation itself was relatively simple and the lack of a direct comparison limits the transfer to naturalistic traffic, distinct changes in observable actions and subjective experience support future research on this topic.

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