A Neurobehavioral Study of Bus Crowding Valuations in Picture-Based and Immersive Choice Experiments

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SHORT SUMMARY

This paper investigates how picture-based and virtual reality (VR) experiment formats influence individuals' valuation of bus crowding in stated preference settings and explores the cognitive mechanisms underlying perception heterogeneity. Thirty-eight participants completed 40 choice scenarios in each format. We estimate individual-level crowding multipliers, that is, the ratio of travel time valuation in crowded versus uncrowded scenarios, across both formats and investigate their correlations with neural biomarkers. Our analysis reveals no differences in crowding multipliers across experiments. However, EEG analyses indicate distinct cognitive processes: the picture-based experiment is associated with enhanced top-down control, reflecting greater reliance on internal beliefs and prior experiences (elevated frontal alpha-band activity). This finding is further supported by the association between crowding multipliers and self-reported willingness to avoid crowding in the picture-based experiment, whereas no such association is observed in the VR-based experiment.

Keywords: Crowding valuation; Crowding multiplier; Virtual reality; Brain data.

1. INTRODUCTION

A growing body of evidence shows that crowding valuations vary across travelers, driven by travel frequency (Aghabayk et al., 2021), trip purpose (Batley et al., 2019), personal attitudes (Márquez and Poveda, 2019), and socio-demographics (Hong et al., 2024; Tirachini et al., 2017). To assess crowding valuation, most studies estimate crowding multipliers, defined as the ratio of the value of travel time in the crowded condition relative to the uncrowded one. Although previous studies have investigated heterogeneity in crowding multipliers across travelers using both stated preference (SP) data (Márquez and Poveda, 2019; Aghabayk et al., 2021; Rossetti and Daziano, 2024) and, more rarely, revealed preference (RP) data (Tirachini et al., 2016; Yap et al., 2020; Bansal et al., 2022a; Kapatsila et al., 2025), the neurobehavioral mechanisms underlying this heterogeneity remain overlooked.

Prior research on crowding has mostly relied on SP experiments, which may exhibit hypothetical bias and lead to deviations from real-world behavior (Mokas et al., 2021; Rid et al., 2018). Virtual reality (VR) is emerging as a promising tool for enhancing the realism of choice situations, and systematic comparisons between VR and other experimental formats have become a growing trend in the urban and transportation planning literature (Patterson et al., 2017; Yin and Cherchi, 2024). In the crowding valuation literature, only a few studies have conducted experiments in VR (Sadeghi et al., 2023a; Sadeghi et al., 2023b), and they provide no conclusive evidence that VR is inherently superior to image-based SP experiments.

Therefore, in this paper we address the following research questions. First, we explain the heterogeneity in crowding multipliers across travelers by estimating the relationship between their crowding multipliers and brain activity. Second, we test whether the type of experiment affects crowding perception by comparing crowding multipliers and brain activity across similar experiments conducted in VR and in a picture-based format. Finally, we test whether the relationship between crowding multipliers and brain activity differs between VR and picture-based experiments.

2. METHODOLOGY

Participants and experimental design

Thirty-eight participants (19 males and 19 females; mean age = 23) were recruited from the National University of Singapore. Sample size aligns with comparable EEG-based transportation studies (Maksimenko et al., 2025). The study was approved by the institutional ethics committee (NUS-IRB-2023-944).

The experiment consists of two parts. In the first part, we collected data on participants' subjective valuation of crowding using an average score derived from a five-question survey on a five-point Likert scale, capturing five distinct behavioral dimensions related to crowding avoidance as stated below. In the second part, participants completed a binary choice task in both picture-based format on a monitor (Fig. 1A) and VR-based format (Fig. 1B), choosing between two buses based on travel time and crowding level. An illustration of a choice situation is shown (see Fig. 1C).

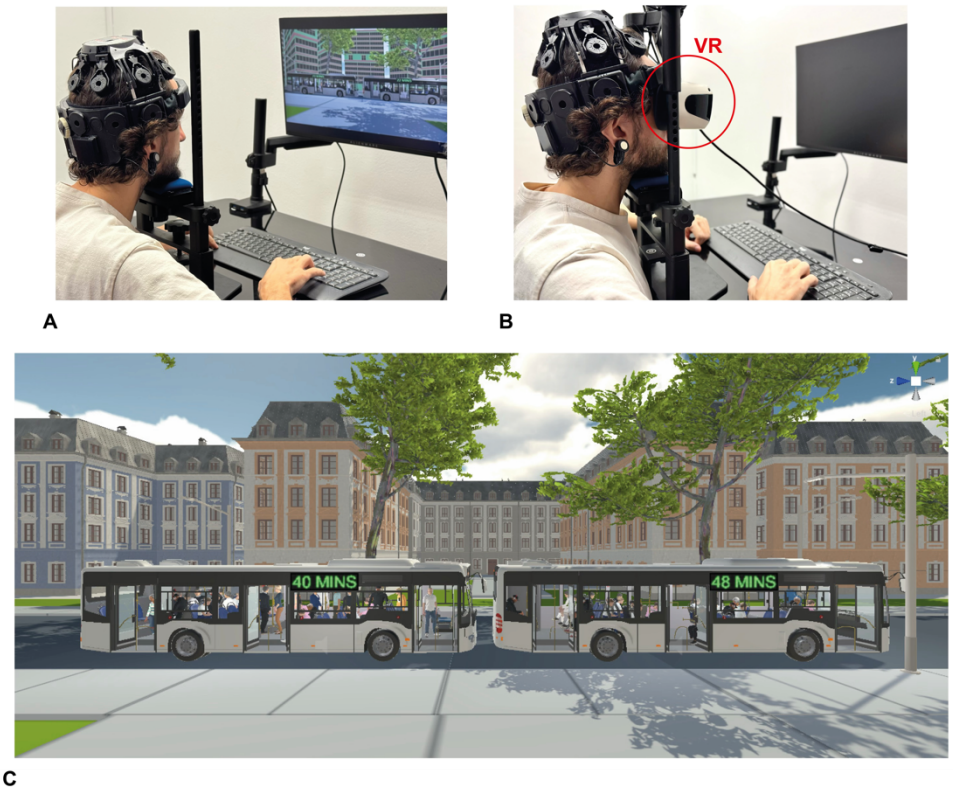


Figure 1. Experimental setup for assessing crowding perception using EEG. (A) Picture-based experiment. (B) Virtual reality-based experiment. (C) Example of a choice situation (medium crowding on the left bus vs no crowding on the right bus).

Crowding level was shown through the density of people inside the bus and took three levels: no (0 pax/m²), medium (3 pax/m²), and high (6 pax/m²), consistent with Bansal et al. (2019). Travel time was shown on the bus and it ranged from 20 to 40 minutes for short journeys and 40 to 60 for long journeys, with five increase levels (10%, 20%, 30%, 40%, and 50%) relative to base. Each crowding-level comparison (no vs medium, medium vs high) was paired with five travel-time saving scenarios for short and long trips. In each choice situation, more crowded bus offered shorter travel time and less crowded bus offered longer travel time. This yielded in 20 unique scenarios; each was repeated with counterbalanced bus order, resulting in 40 situations per participant per format.

Choice scenarios were designed in Unity. The VR- and picture-based experiments utilized identical static visual stimuli (screenshots from VR were shown in the picture-based experiment), ensuring that any observed differences could be attributed to the level of immersiveness rather than dynamic presentation. To control for order effects, half of the participants (N = 19) completed the VR block first; the other half began with the picture-based block. The 40 choice situations were fully randomized within each block. Between VR and picture-based blocks, participants were given a break for 5 minutes.

EEG data collection and analysis

Brain activity was recorded using multichannel EEG with 18 dry sensors arranged according to the standard 10–10 system at a sampling frequency of 300 Hz, providing coverage of frontal, central, parietal, temporal, and occipital regions.

Raw EEG signals were re-referenced to the common average, bandpass filtered between 4 and 30 Hz, and cleaned using independent component analysis. EEG signals were segmented into 20-second trials time-locked to scene onset.

EEG activity was quantified using wavelet power averaged across three frequency bands: theta (4–8 Hz), associated with cognitive control and mental workload (Kakkos et al., 2021); alpha (8–13 Hz), shows whether participants rely more on external sensory information or on prior experience (Bonnefond and Jensen, 2012; Jauk et al., 2012; Klimesch, 2012; Van Diepen et al., 2019). and beta (13–30 Hz), linked to affective processing (Schubring and Schupp, 2019, 2021) and has recently been used in transportation research to identify the effect of emotions on the evaluation of ethical decisions involving autonomous vehicles (Maksimenko et al., 2025). Event-related spectral perturbation (ERSP) was computed as the relative change in wavelet power during the choice process compared to the 4-second baseline.

Modelling

Given that each participant completed 40 choice tasks, the data exhibits a panel structure where observations from the same individual are correlated. Therefore, our analysis relies on mixed multinomial logit (MXL) model that explicitly accounts for intra-individual correlation and unobserved heterogeneity in taste preferences (Train, 2009). We estimated MXL with 1,000 Halton draws using the maximum simulated likelihood approach (Train, 2009). All models were estimated using the Apollo package in R (Hess and Palma, 2019). Then, crowding multiplier is calculated by taking the ratio of the marginal utility of travel time under crowded conditions to that under non-crowded conditions.

3. RESULTS AND DISCUSSION

Crowding Multipliers in VR and Picture-based Experiments

The distribution of crowding multipliers across VR and picture-based experiments is shown in Fig. 2, showing the heterogeneity in crowding multipliers across individuals. The comparison of the ECDFs of the estimated crowding multipliers under VR and picture-based experiments is shown in Fig. 3. Both VR and picture-based formats exhibit increased crowding multipliers as crowding level rises, with picture-based showing slightly higher crowding multiplier values. The shaded regions representing the 5th–95th percentile confidence intervals largely overlap between VR and picture-based at each crowding level, which indicates that the observed differences in crowding multiplier distributions are not statistically significant.

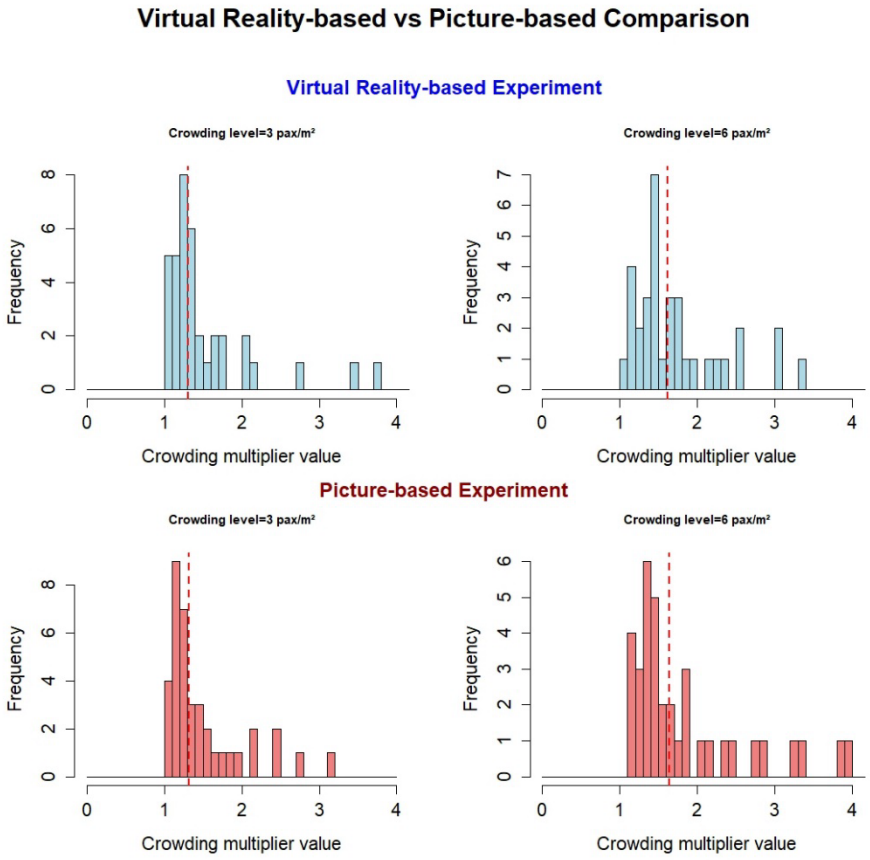


Figure 2. Histograms of crowding multipliers for each experiment type corresponding to crowding level (pax/m^2) using MXL model. The red dotted vertical line represents MNL estimates.

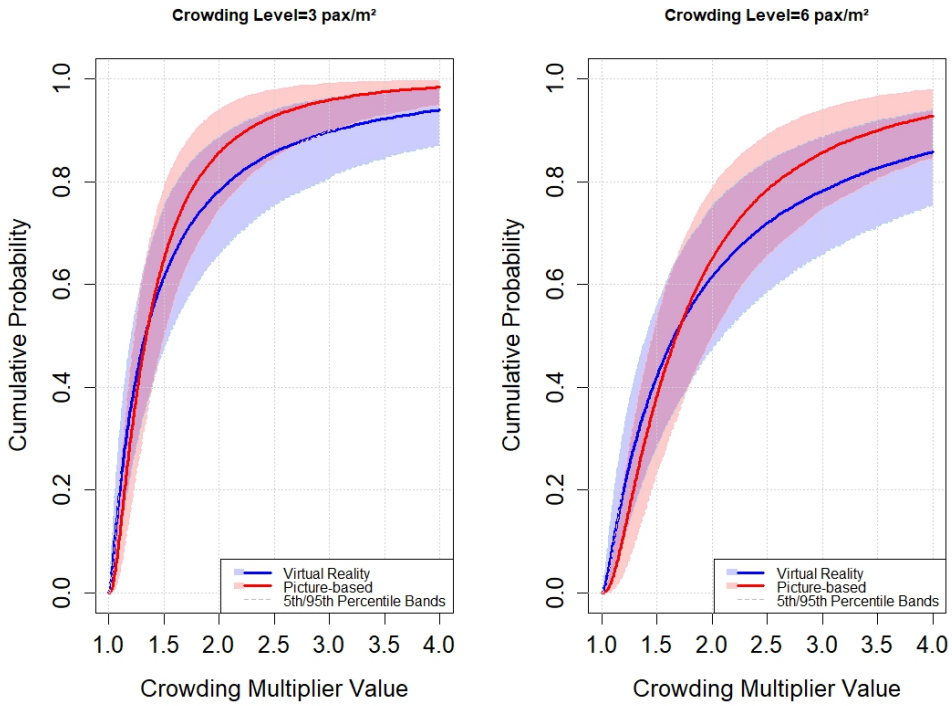


Figure 3. Comparison of the empirical cumulative distribution function (ECDF) and 90 % confidence interval of crowding multipliers for each experiment type corresponding to the crowding levels (pax/m^2).

Reflection of Subjective Crowding Valuations

We then use Spearman's rank correlation to assess the association between this subjective crowding valuation score (see Methods) and the crowding multipliers estimated in the picture-based and VR-based experiments (Fig. 4).

We observe a strong positive and statistically significant correlation between subjective valuation and the crowding multipliers in the picture-based experiment ($r = 0.48$, $p < 0.01$). In contrast, the correlation between these variables in the VR-based experiment is lower and not statistically significant at the 0.05 level ($r = 0.28$, $p = 0.09$). These results suggest crowding multiplier estimates in the picture-based experiment more closely reflect the subjective valuation of crowding than the VR-based experiments.

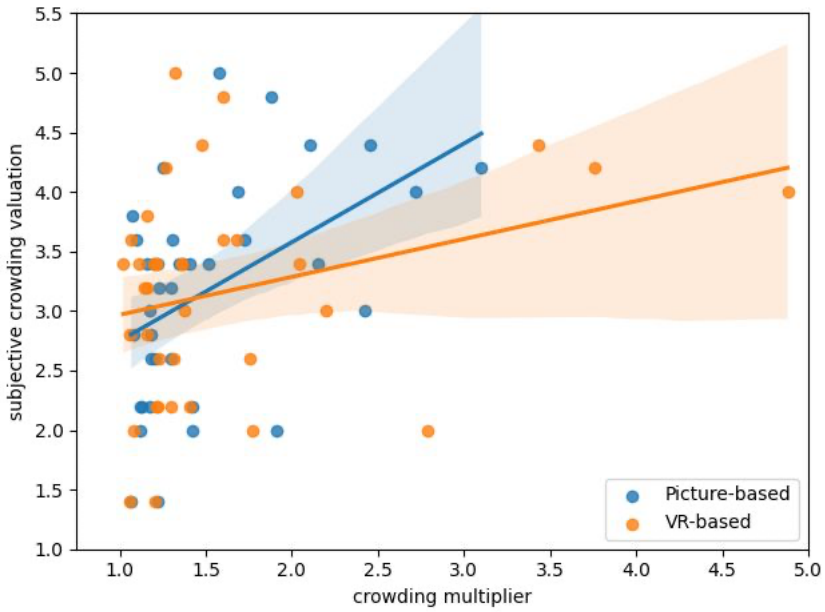


Figure 4. Correlation between estimated crowding multipliers in the picture-based and VR-based experiments and a subjective survey-based assessment of the crowding perception (data are shown as regression line with 95% CI and subject-level observations).

Brain activity in the picture-based and VR-based experiments

In the theta-frequency band (Fig. 5A), the Wilcoxon test did not reveal any significant differences between the two experimental formats at any sensor. The z-values ranged from 0.11 to 1.63 (Fig. 5B), none of which exceeded the significance threshold of 1.96 ($p = 0.05$).

In the alpha-frequency band, the frontal alpha-band ERSP was significantly higher in the picture-based experiment than in the VR-based experiment (corrected p-value < 0.05, Wilcoxon test). Elevated frontal alpha-band activity is widely interpreted as a neural correlate of inhibitory control and the redirection of attention from external stimuli toward internally generated information (Bonnefond and Jensen, 2012; Jauk et al., 2012; Klimesch, 2012; Van Diepen et al., 2019). In line with these studies, our findings suggest that in the picture-based experiment, individuals exhibiting stronger frontal alpha power rely more heavily on internally generated representations, such as prior experiences and expectations, while suppressing detailed processing of external visual information. This pattern is consistent with decision-making in less immersive environments, where reduced sensory richness may encourage greater top-down control and internalized evaluation processes.

In the beta band (Fig. 5E), the Wilcoxon test did not find any significant differences at any sensor; z-values ranged from 0.21 to 1.93 (Fig. 5F), all below the threshold of 1.96.

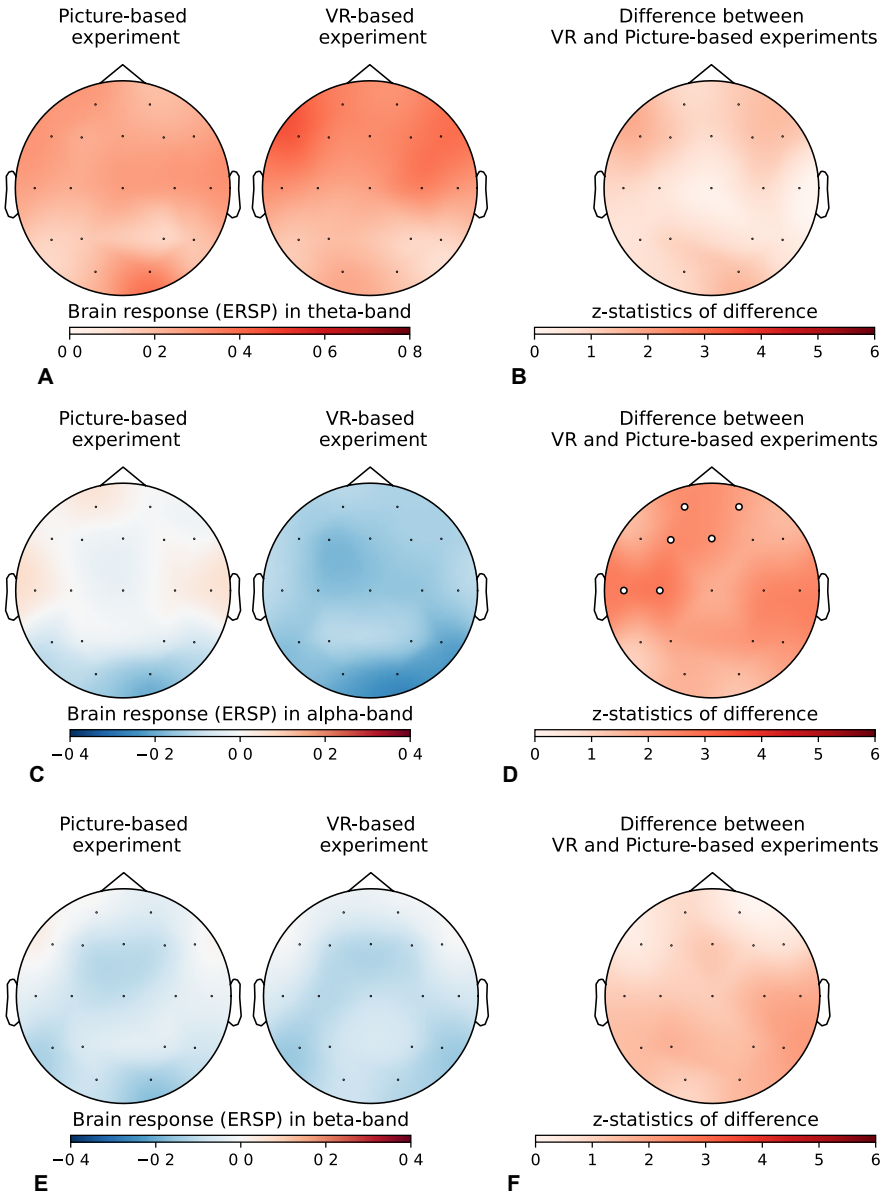


Figure 5. Topographic distribution of the ERSP across EEG sensors in picture-based and VR-based experiments in the theta (A), alpha (C) and beta (E) frequency bands. Topographic distribution of the z-value as a result of Wilcoxon test of the difference in ERSP between picture-based and VR-based experiments in the theta (B), alpha (D) and beta (F) frequency bands. Those EEG sensors, where the difference is significant (based on the permutation correction) are marked by circles.

Brain activity variation across participants

To investigate why differences in alpha-band do not result into differences in crowding multiplier estimates across VR and picture-based experiments, we investigate cognitive processes that could potentially explain variability of the crowding multipliers across participants. To this end, we estimate the correlation between ERSP and crowding multiplier in both the picture-based and VR-based experiments across all frequency bands at each EEG sensor. We found that ERSP in beta band across frontal, central, and occipital sensors is positively correlated with estimated crowding multipliers in picture-based experiment, but not in VR experiment. These results are consistent with a statistically significant and stronger correlation between the crowding multiplier and subjective crowding valuation in the picture-based experiment than in the VR experiment.

4. CONCLUSIONS

Our analysis revealed that the estimated distributions of crowding valuation are statistically indistinguishable from those obtained using picture-based experiments. However, EEG analyses revealed distinct cognitive processes: the picture-based condition was associated with enhanced top-down control reflecting greater reliance on internal beliefs and prior experiences (elevated frontal alpha-band activity), consistent with the observation that between-participant heterogeneity in crowding multipliers in the picture-based experiment was significantly associated with self-reported willingness to avoid crowding, whereas no such association was observed in the VR-based experiment.

These findings suggest that picture-based surveys amplify the influence of intrinsic attitudes on stated preferences, while immersive VR presentations may instead direct participants' attention toward the attributes of the choice task itself. As a result, picture-based SP designs may therefore be suitable when the objective is to capture attitudinal heterogeneity, while VR-based experiments may be better suited for isolating situational effects of crowding or evaluating design interventions where realistic spatial perception is critical.

ACKNOWLEDGEMENTS

Prateek Bansal was supported by Presidential Young Professorship grant.

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