Affective experience in a virtual crowd regulates perceived travel time

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Abstract

Time sometimes feels like it is flying by or slowing down. Previous research indicates objective number of items, subjective affect, and heart rate all can influence the experience of time. While these factors are usually tested in isolation with simple stimuli in the lab, here we examined them together in the ecological context of a virtual subway ride. We hypothesized that subjective affective experience associated with objective crowding lengthens subjective trip duration. Participants (N=41) experienced short (1-2 minutes) immersive virtual reality subway trips with different levels of public crowding. Consistent with the immersive nature of decreased interpersonal virtual space, increased crowding decreased pleasantness and increased the unpleasantness of a trip. Virtual crowding also lengthened perceived trip duration. Presence of one additional person per square meter of the train significantly increased perceived travel time by an average of 1.8 seconds. Degree of pleasant relative to unpleasant affect mediated why crowded trips felt longer. Independently of crowding and affect, heart rate changes were related to experienced trip time. These results demonstrate socioemotional regulation of the experience of time and that effects of social crowding on perception and affect can be reliably created during a solitary virtual experience. This study demonstrates a novel use of Virtual Reality technology for testing psychological theories in ecologically valid and highly controlled settings.

Keywords: Time perception, crowding, virtual reality, emotion, heart rate

Introduction

If we consider time as one dimension of existence, then passage of each and every moment is like moving forward but in time rather than space. In this analogy, we are all constantly traveling in time, moving from one moment to the next. However, the pace of this time travel is subjectively variable depending on various perceptual, cognitive, and emotional factors. Time appears to slow down during an accident (Arstila 2012). A trip from home to a shopping mall feels longer than the return trip, even though they have the same objective distance and duration (van de Ven, van Rijswijk, and Roy 2011). This latter example is a situation of traveling both in time (as we always do) and space (between two places), showing that a spatial trip can feel longer or shorter depending on the subjective perspective. Here, we examined a socioemotional relativity of travel time in a virtual subway car examining whether objective vs subjective factors regulated experience of time. We tested the effect of density of individuals in the limited space, i.e., crowding, on subjective affect and cardiovascular arousal and perceived travel time of public transit commutes in an immersive Virtual Reality (VR) environment.

Several variables associated with an altered perceived duration of an interval include objective stimulus factors such as complexity (Aubry et al. 2008; Roelofs and Zeeman 1951;

Schiffman and Bobko 1974), and numerosity (Dormal, Seron, and Pesenti 2006; Hayashi, Valli, and Carlson 2013; Xuan et al. 2007), as well as internal factors such as emotion (Droit-Volet 2013; Droit-Volet and Meck 2007; Lake, LaBar, and Meck 2016; Schirmer 2011). Although usually tested with less realistic stimuli, these factors are closely related to a daily-life context, i.e., social crowding. Crowding is an inevitable aspect of urban life with certain perceptual characteristics, such as visual numerosity along with negative emotional influences, especially during the age of COVID-19 pandemic. Both perceptual and emotional aspects of crowding could contribute to a distortion of the perceived time.

Perceptual and cognitive influences of crowding on time perception

The visual aspect of crowding is the view of a higher number of stimuli in a limited space. According to *A Theory of Magnitude,* those questions of how many and how long, how fast, and how far are tightly related to each other (Walsh, 2003). Estimating time, space and quantity share a common underlying system in the parietal cortex (Walsh, 2003), the region that also supports the directing of attention to spatiotemporal features (Coull et al. 2004). Aligned with this theory, various studies have demonstrated that higher magnitude or numerosity of items presented during an interval, lead to a longer perceived duration. For example, a physically larger stimulus has a lengthened duration compared to a smaller stimulus (Rammsayer and Verner 2014; Xuan et al. 2007). Higher numbers of dots are perceived longer than fewer dots (Dormal et al. 2006; Hayashi et al. 2013; Long and Beaton 1981; Xuan et al. 2007). Even a digit is perceived temporally longer the larger the value it represents (Oliveri et al. 2008). Complexity of stimuli has also been shown to increase perceived duration (Aubry et al. 2008; Roelofs and Zeeman 1951; Schiffman and Bobko 1974). More dynamic visual displays with more complex motion are perceived longer compared to more static ones or with simpler movements (Brown, 1931).

Affective influences of crowding on time perception

Crowding is not only a different external perceptual experience, but it also causes an internal subjective unpleasant feeling. In a crowded environment an individual might experience a violation of personal space, which serves as an imaginary buffer around the self. When personal space is violated, our defense systems, which have evolved to deal with threats to physical survival, are likely to be activated (Todd and Anderson 2009). This is only more prevalent in the age of the COVID-19 pandemic, where personal space (6ft or less) highlights potential viral exposure. Activating defense systems generates tense arousal, leading to avoidant motivational states. Social crowding in public transit is indeed associated with negative arousal (Cheng 2010; Cox, Houdmont, and Griffiths 2006; Kalb and Keating 1981; Stokols 1972), with feelings of discomfort, distraction, frustration, and irritation along with somatic symptoms such as headache, tension, and stiff muscles (Mahudin, Cox, and Griffiths 2011, 2012).

Emotions are connected with the perception of time (Droit-Volet 2013, 2018; Droit-Volet and Meck 2007; Lake 2016; Lake et al. 2016; Schirmer 2011). In fact, perception of duration is sometimes described as accumulation of bodily physiological and emotional moments across time (Craig 2009). Negatively arousing stimuli are perceived longer in duration than neutral stimuli (Droit-Volet, 2013). For instance, a sound that induces negative affect is perceived longer than a neutral one (Noulhiane et al. 2007). These effects of negative valence may also reflect the intensity of valence experience, whether positive or negative, strongly associated with self-reported arousal

(Kron et al. 2015), which is associated with attentional engagement and modulation of online (perception) and offline (memory) information processing (Riggs et al. 2011). The exact mechanisms of affective modulation of time perception, however, are still debated (Lake et al. 2016).

Peripheral physiological correlates of time perception

In the most prominent model of time perception, the pacemaker accumulator model, dilation of time in emotional contexts is thought to reflect arousal increasing the rate of the internal clock (Treisman et al. 1990), similar to how emotions regulate the peripheral cardiac pacemaker to alter heart rate (Cacioppo et al. 2000). Previous studies have examined the relation between time perception and autonomic states that regulate physiological pacemakers, such as heart rate (Schwarz, Winkler, and Sedlmeier 2013). The homeostatic time perception theory associates temporal perception with integration of bodily signals over time (Craig 2009). Based on this theory, dilation of duration in emotional conditions may be linked to the integration of peripheral physiological signals such as heart rate (Craig 2009; Meissner and Wittmann 2011).

The heart has been of particular interest compared to other physiological measures due to its rhythmic behavior and having both sympathetic and parasympathetic innervation, affording both the slowing and speeding up of its pacemaker. Several previous studies estimated average heart rate as a measure of bodily arousal hypothesizing that it increases the speed of the internal clock (Bell and Provins 1963; Osato, Ogawa, and Takaoka 1995; Schwarz et al. 2013). A few studies used other measures such as slope of change in heart rate during an interval (Angrilli et al. 1997; Meissner and Wittmann 2011). The results of these studies have been mixed, and the relationship between heart rate and time perception is still controversial (Ogden et al. 2022; Otten et al. 2015; Schwarz et al. 2013).

Current study

As reviewed above, physical and affective characteristics that are associated with social crowding are shown to lengthen experience of time; these dimensions are examined in isolation, commonly with computerized stimuli such as geometrical shapes or images. It is unknown whether these factors scale up to more complex real-world conditions, and for situations of consequence for choice and behavior. Beyond the ability to accurately estimate the passage of time, how do objective external or subjective internal factors modulate distortions in subjective time in a real-world setting? Here we examined the objective factors of passenger density to regulate an internal subjective factor related to crowding discomfort. We hypothesized that social crowding in an ecologically valid virtual context leads to negative feelings which in turn leads to a lengthened perceived travel duration. To examine this hypothesis, we used immersive VR technology, simulating a realistic social setting with controlled manipulation of crowding levels, i.e., number and closeness. While participants were physically in the lab, they experienced short (1 to 2 minutes) immersive trips in the VR environment of a subway train with specific densities of virtual passengers sitting or standing around. We examined perception of duration and negative and positive affect after each of 5 virtual trips that had 5 different crowding levels (**Fig. 1**). By separately assessing positive and negative valence, we could assess their relative and combined contributions (Kron et al. 2015) to time perception. We also examined changes in heart rate during the virtual trips to control and explore the potential link between objective physiological changes and subjective travel time perception.

We tested two main hypotheses: H1: there is an effect of crowding on time perception: perceived duration increases with an increase in crowding level. This may reflect perceptual, cognitive, or affective aspects, as reviewed above. H2: The effect of crowding on time perception is mediated by internal affective responses, such that crowding may lengthen subjective time through the route of negative experience. That is, crowding distorts time perception to the degree it generates an internal negative experience. We further explored two cardiac measures and their association with perceived duration during the interval (here, called the “trip”): average heart rate and slope of change in heart rate. The heart rate analysis was more exploratory rather than hypothesis-based due to the inconclusive cardiac effects in previous studies.

Methods

2.1. Participants

Forty-two individuals were recruited at the Ithaca campus of Cornell University to participate in the experiment. Student volunteers received extra course credit as compensation for their participation. All participants tolerated the VR experience except for one participant who did not finish the experiment due to feeling nauseous. All other individuals were included in further analysis (N=41). Participants were between 19 and 51 years of age (M=22.6, SD=5.5), and consisted of 19 females. All participants gave informed consent in accordance with the Institutional Review Board at Cornell University, in accordance with principles outlined in the Declaration of Helsinki and its later amendments. Data collection was performed prior to the COVID-19 pandemic in fall and winter of 2018.

2.2. VR environment

The VR environment was developed to simulate the inside of a subway car, including moving avatars of passengers **(Supplementary video)**. The dimensions and the interior of the subway car were created to represent the New York City subway car R160 model (13.61m × 2.59m, 35.25m^2) currently in service. Five conditions were used in the experiment to present five different levels of passenger density.

The number of passengers in the car in each condition was determined to have one, two, three, four, and five passengers per square meter. For example, the lowest density condition was created with one passenger per square meter, i.e., 35 passengers in 35 m^2, and the highest density condition was with five passengers per square meter, i.e., 175 in 35m^2. Seating and standing passengers were placed with random distributions to look natural while keeping the total number in the car in the incremental ratios.

The 3D computer model of the environment was created in Autodesk 3DS Max, then converted into Twinmotion software where real-time interaction and avatars were added. Interactions allowed a viewer to walk in the subway car and look around the environment and passenger avatars. The avatars were animated to simulate naturalistic behaviors of passengers such as occasionally changing postures, looking at phones, and reading books or magazines.

To experience the virtual environment, we used the HTC VIVE Virtual Reality system with the VR headset (www.vive.com). VIVE display has a resolution of 2,160 × 1,200 (1,080 × 1,200 per eye), 90 Hz refresh rate, and 110 degrees field of view. The experiment was run in the Twinmotion 2018 standalone player on a lab workstation capable of running 3D graphics with an NVIDIA GTX 1070 graphics card.

Fig. 1 presents the top view of each condition with a screenshot of an eye-level camera view. All sounds during the VR experience were played using a speaker within one meter distance to the participant's standing point. The sounds were identical for all crowding conditions with equivalent volume. Participants heard the noise of a moving train as they were in the VR environment for the duration of the trip (**supplementary video and audio**). All audio clips were equivalent in sound volume.

2.3 Procedure

The experiment included a number of virtual trips on a subway car. For all trips, the participants first wore the VR headset with the help of the experimenter and found themselves immersed in the VR subway-car environment. Trips started with the recorded standard New York City subway announcement saying "stand clear of the closing doors please," followed by a bell ringing and sound of a subway car starting to accelerate. The trip ended with another bell-ringing sound. All trips were similar, except in the duration and the density of the virtual crowd on the subway car (5 density levels). Participants were informed that the trip duration is the time between the first bell and the second bell ringing sounds.

Upon arrival at the lab and signing the consent form, participants were given an oral description of a trip. They then experienced three practice trips with density levels 1, 3, and 5 (with random order) and of 100 second duration. The purpose of the practice trip was to familiarize them with the environment and the concept of a virtual trip. During demo runs, participants were asked to estimate the duration following the trips. They did not receive any feedback about the accuracy of their estimates. After the demo trips they performed the main VR task and then answered several surveys about transportation preferences. All questions asked during the VR task and the following surveys were computer administered through the Qualtrics online survey platform.

2.4. VR task

The VR task included experiencing 5 trips with all 5 different passenger density levels in a randomized order, each having a randomly selected duration among 60, 70, or 80 seconds (with equal probability). This variation in trip length allowed us to assess perception of objective duration and created variability to encourage perception rather than guessing. After each trip, participants were asked to take off the headset and sit at a computer to answer questions about their experience. These questions included the following:

1) Indicate how *pleasant* you felt during the virtual trip experience you just had, by a number between 1 and 7.

2) Indicate how *unpleasant* you felt during the virtual trip experience you just had, by a number between 1 and 7.

3) How long was the trip you just experienced? Type your estimate in seconds.

Pleasantness and unpleasantness were asked in two unipolar scales (questions 1 and 2), which unlike bipolar scales (negative to positive) allowed for assessment of mixed feelings and while also allowing derivation of overall subjective affect (sum of positive and negative valence) which very closely approximates self-reported and physiological arousal (Kron et al. 2013, 2015). Bivariate valence was defined as the separate ratings of pleasantness and unpleasantness. Net valence was defined as pleasantness rating (question 1) minus unpleasantness rating (question 2). Overall subjective affect was estimated by summing pleasantness and unpleasantness ratings.

2.5. Physiological recording and analysis

Cardiac data were recorded during the experiment using the Empatica E4 wristband. E4 is a wireless Bluetooth wearable device that detects pulse using Photoplethysmogram (PPG). Participants were instructed to rest their hand on a stand during the virtual trip (**supplementary video**) in order to reduce movement of the wristband and prevent noise in physiological data. Interbeat intervals (IBI) are the duration of the interval between two consecutive heartbeats. IBI's recorded during each trip were extracted based on the logged start and end time of the trip. Average IBI for each trip (i.e., inverse of heart rate), was then estimated as an inverse measure of autonomic cardiac activation during the trip. We also estimated the average slope of change in heart rate during each trip using a linear model with timestamp of each beat as the independent variable and the corresponding IBI as the dependent variable.

2.6. Statistical analysis

We used mixed-effects regression models for statistical analyzes since the task design consisted of repeated measures for each participant. These models account for both within and between subjects' variability, by including a random intercept that depends on subject ID in addition to fixed effects for conditions. We used these models for all tests on the relationship between trip-related measures (unless otherwise stated), for example, testing whether crowding would explain affect or time perception bias or in models ran for the mediation analysis. Statistical significance of models fixed-effects (slopes of independent variables) were estimated using t-tests with Satterthwaite's method to approximate degrees of freedom. Whether the average of a trip measure such as time perception bias was different from zero was tested using a random effect model predicting the variable from an intercept (significance of intercept would show systematic difference of the variable from zero).

All data analysis was performed using the R programming software. The *gmnl* package in R was used for mixed effects regression analysis and the *mediation* package (Tingley, Yamamoto, Hirose, Keele, & Imai, 2014) for estimating the direct and indirect effects in the mediation analysis.

Results

Each participant experienced five VR trips with five different crowd density levels (**Fig. 1**; also see **supplementary video**). The pleasantness and unpleasantness of trips averaged for each density level is represented in **Fig. 2a**. Overall the travel experience was largely pleasant, particularly at low density levels. Net valence of an experience defined as pleasantness minus unpleasantness decreased, as a function of increase in density level (β=-1.03, SE=0.099, $p<0.0001$**)**. This was driven by both a decrease in pleasantness (β=-0.51, SE=.067, $p<0.0001$) and an increase in unpleasantness ratings as a function of crowding (β=0.52, SE=0.069, $p<0.0001$). However, overall subjective affect, estimated by summing of the pleasantness and unpleasantness ratings, was not significantly predictable from density ($\beta=2.4*10^{-3}$, SE=0.033, p=0.94). As such, overall subjective affective activation level did not differ across density levels, but rather, crowding was strongly associated with a shift away from net pleasantness.

Participants were able to assess objective differences in temporal durations, with perceived duration increasing with objective duration of the train ride (β=0.76, SE=0.14, $p<0.0001$). We defined a measure of *time perception bias* as the actual duration of a trip subtracted from the participant's perceived duration. **Fig. 2b** represents mean bias in time perception (in seconds) for each density level. Time perception bias was on average significantly negative (β=-10.88, SE=4.81, p=0.029), indicating a tendency towards underestimation. Consistent with H1, crowding level predicted a temporal bias in trip duration (β=1.81, SE=0.74, p=0.016). durations with less crowding were most underestimated, which was lessened with increased crowding. As such, subjective perception of trip duration increased with increased crowding; and conversely, decreased with more interpersonal distance. This trend, however, was not followed between the crowding levels 4 and 5, with level 5 having a slightly lower time perception bias, though the difference was not significant (p=0.6). Summary statistics of the pleasantness, unpleasantness, and time perception bias ratings for different crowding levels are represented in table 1.

An individual's bias in travel time could also be predicted from the feelings about the trip (**Fig. 2c**). There was a significant effect of valence in predicting time perception bias, with more unpleasant or less pleasant trips (more negative valence) being perceived to be longer (β=-1.60, SE=0.44, p=0.0003). By contrast, an individual’s feelings about the trip could not be predicted from objective differences in travel duration ($\beta=-4.1*10^{-4}$, SE=0.02, p=0.99). That is, objective trip duration did not modulate feelings, but conversely, subjective feelings did modulate the amount of bias in subjective trip duration. Objective passage of time was not related to subjective experience of feelings. Feelings were, however, related to subjective experience of time.

Both density and subjective affect predicted the extent to which observers were *biased* in perceiving trip duration. That is, objective crowding and subjective affect predicted subjective bias in trip duration. Further mediation analysis was conducted to examine H2 whether degree of subjective affective experience (unpleasantness minus pleasantness) mediated the relationship between crowd density and time perception bias. We chose to use net valence given the substantial collinearity between unpleasantness and pleasantness. The overall subjective affect (pleasantness plus unpleasantness) was also not a feasible mediator given that it was not predictable from crowd density. Results of the mediation analysis are presented in **Fig. 3**. Results revealed a significant mediation effect (estimate=1.55, 95% confidence interval=(0.46, 2.63), $p<0.0001$), and no remaining direct effect of crowd density (estimate= 0.16, 95% confidence interval=(-1,72, 1.57), $p=0.82$). The impact of time perception bias was no longer significant when affect was included in the model that predicted time perception bias from crowding level (standardized crowding $\beta=0.01$, $SE=0.04$, $p=0.4$). Therefore, the subjective affective valence mediated the effect of crowd density on time perception bias.

Analysis of the cardiac activity data during trips did not show a significant relation between the average Inter-Beat Interval (IBI) and crowding level ($\beta=0.001$, $SE=0.014$, $p=0.36$), actual travel time ($\beta=-2.1*10^{-4}$, $SE=2.2*10^{-4}$, $p=0.35$), bias in perceived travel time ($\beta=5*10^{-6}$, $SE=1.4*10^{-6}$, $p=0.96$) or experienced valence ($\beta=-0.091$, $SE=0.20$, $p=0.66$). As such, the effects of crowding on subjective trip duration could not be explained simply by altered cardiac activity. However, an exploratory analysis revealed a significant overall decrease in IBI within a trip ($\beta=-5*10^{-4}$, $SE=8.7*10^{-5}$, $p<0.0001$), indicating an increase in heart rate. As shown in **Fig. 4,** a larger slope of this IBI change, i.e., more deceleration or less acceleration of heart rate during the trip, was associated with longer perceived travel duration ($\beta=3870$, $SE=1721$, $p=0.026$). This was the case even though the IBI slope was not explained by the objective crowding level ($\beta=1.5*10^{-5}$, $SE=3.9*10^{-5}$, $p=0.70$), or subjective valence of the trip ($\beta=2.8*10^{-8}$, $SE=2.1*10^{-5}$, $p=0.90$). IBI slope's effect on perceived travel duration was significant even when controlling valence (slope $\beta=3746$, $SE=1704$, $p=0.029$); therefore, heart rate had a unique contribution to variability in perceived trip duration.

Discussion

In a VR simulation of a subway ride, we examined the relationship between density of passengers and perceived duration of short immersive trips. Results showed that crowding level inside the subway car had a significant effect on one's perception of travel time: one additional passenger per square meter on average increased perceived duration of a 1-2 minute trip by around 1.8 seconds. This effect was explained by subjective feelings. While passenger density is an objective measure (here only a visual factor), it regulated the subjective internal senses of the passage of time and affective feelings. Increased virtual crowding made a trip feel longer and more unpleasant. It was this latter subjective feeling that mediated the former effect of crowding on time perception: A more crowded trip was perceived longer to the extent that it induced more negative and less positive feelings. This result is in agreement with previous evidence that negative emotions lengthen perceived duration (Droit-Volet 2013; Droit-Volet, Brunot, and Niedenthal 2004; Noulhiane et al. 2007; Rey et al. 2017), indicating that crowding, as an affectively negative factor could have such an effect on time perception. Conversely, a less crowded trip was judged as a more positive experience. Indeed, the temporal bias associated with unpleasant experience of virtual crowding resulted in a closer approximation of objective duration (see **Fig. 2b, 2c**). As such, positive experiences were associated with a relatively greater contraction of time; that is, time flew by, i.e., greater contraction relative to objective duration, the more pleasant the trip.

While we found a relationship between self-reported affect and estimated time, objective trip duration did not alter self-reported affect. That is, objective trip duration did not alter subjective feelings, but feelings did regulate the subjective experience of trip duration. In terms of causal direction, the physical dimension of time was strongly associated with felt time, but not felt affect. As such, felt time did not cause affect, but affect regulated the experience of the subjective passage of time. This is consistent with subjective time as being regulated by internal states, or affective moments. This would also provide support for an ecological view of time (Post 2019), as a resource related to homeostatic mechanisms reflected in the experience of valence (Barrett and Simmons 2015). In this way, distortions in time perception reflect the passage of affective moments (Craig 2009).

Independently of crowding and subjective affect, analysis of the cardiac activation showed a significant increase vs decrease change in heart rate during a trip, suggestive of sympathetic arousal and stress relative to relaxation (Kirschbaum, Pirke, and Hellhammer 1993). This relative change in heart rate also contributed to lengthened vs shortened perceived travel time. Sympathetic heart rate acceleration facilitates action in an urgent situation (fight or flight), while the parasympathetic deceleration facilitates higher sensory intake during passive attention (Graham and Hackley 1991; Vila et al. 2007). Our results, therefore, suggest that in this sympathetic-parasympathetic compromise, a less sympathetic or more parasympathetic dominance is associated with a lengthened perception of time. As this effect was independent of the effect of valence on perceived travel time, the role of heart rate change is probably a marker of central attentional rather than affective processes. This finding is aligned with an ample amount of evidence that increased attention lengthens subjective time (Grondin 2010).

The effect of crowding on time perception was strongly mediated through the route of affective valence. However, it is possible that other cognitive, perceptual, or emotional factors also play a role. One specific component related to the unpleasantness of crowding could be a sense of "suffering," i.e., the endurance of negative feelings. The longer estimated duration of a trip may originate from one's desire to end the trip sooner and leave the unpleasant environment. In other words, when answering "how long did you perceive the trip?" participant's response may be impacted by a subjective assessment of "how much did you wait for the trip to end sooner?." Hence, the lengthened duration of the trip, its unpleasantness, and the sense of desire to end the trip may be closely related. Waiting for an interval to end has been previously associated with lengthened perceived duration, and this effect has been associated with increased attention to time when waiting (Witowska, Schmidt, and Wittmann 2020). However, given that the trips were judged to be highly pleasant and only moderately unpleasant with greater crowding, the urge for the trip to end was unlikely. Further research is required to distinguish the desire to end an experience, and other specific emotions, from other unpleasant components of a crowd and their impact on time perception.

Despite the overall linear increase in perceived duration with increase in crowding, the trend did not follow between the highest crowding levels (**fig 2.b**). This nonmonotonicity of trip duration with the highest crowding level was not significant and hence the deviation from the trend could be merely due to noise. Another, more speculative proposal is that this is the point where unpleasant feelings overtake pleasant feelings, and that the effect of crowding reflects degree of mixed feelings as indexed by the minimum value of positive and negative affect (Berrios, Totterdell, and Kellett 2015). This would be consistent with both pleasant and unpleasant having a role in the regulation of time perception.

The present study did not include an assessment of spatial presence (Baños et al. 2004) as a manipulation check of the virtual aspect of the experience. This is a limitation of our ability to specifically measure immersion. However, rather than self-report physical spatial immersion, the present study provides strong evidence of socioemotional regulation via virtual interpersonal space, i.e., social crowding. The presence, and close presence, of virtual others regulated the experience of affect and was potent enough to regulate the experienced passage of time. This provides further evidence of the capacity for virtual social agents to generate real emotions(Hwang, Yoon, and Bendle 2012; Krijn et al. 2004) and their perceptual and cognitive effects.

Whereas the results revealed a strong effect of crowding on valence, and valence on travel time perception, these effects did not exist for overall affect, our index of subjective arousal level. We used pleasantness plus unpleasantness ratings as an indication of subjective arousal. However, this measure has certain limitations that are worth noting. The unipolar subjective arousal (pleasantness plus unpleasantness) has been shown to be equivalent to the direct arousal when using simple static stimuli, rated shortly after stimulus presentation (e.g. Kron et al. 2015). However, for an interactive virtual trip in the order of minutes, individuals may not sufficiently dissociate their distinct positive and negative mixed feelings. In this case, additional instructions might be needed to encourage subjects to disentangle their mixed feelings. Future studies may examine how different subjective and peripheral measures of arousal are related to the temporal perception in naturalistic settings compared to the measures used here. For instance, the unipolar arousal rating, or the skin conductance response-which specifically measures sympathetic arousal through the sudomotor sweating response-are suggested for future investigation.

The majority of previous experiments on time perception have been administered in the lab setting using computerized tasks with discrete relatively short stimuli. Our experiment took place in the lab as well, but it simulated an experience approximating more closely the ecology of daily life in an urban center. Despite the efficiency of the VR environment in simulating a relatively realistic travel experience, our experiment had several limitations that made it different from daily-life settings. In an actual social setting, crowding has other components such as smell and noise that are beyond the visual closeness to strangers (Haywood, Koning, and Monchambert 2017). Virtual experience with the current VR technology, even though highly realistic, also differs in critical ways from a real experience, including vibratory, kinesthetic, and exterior visual cues that can signal travel time. Although virtual avatars were sufficiently realistic to induce negative feelings by increased density, they were visually distinguishable from real humans. Participants did not actually intend to travel to a destination and were only asked to imagine so. They were also not able to do regular activities people might do on a subway trip such as checking their phone, reading a book, or listening to music, all of which represent ways in which we engage our emotions and attention to regulate the experience of trip duration. Furthermore, the duration of subway trips in the current study were in the range of one to two minutes. This allowed for testing a higher number of conditions in the limited duration of the experiment session, at the expense of having unrealistically short trips. Another limitation for the study is the possible confounds of the previous experience with VR hardware. Participants without previous VR experience, for example, may have an additional excitement about the novelty of a VR experience. The three demo trips were included at the beginning to dampen the emotions caused by the novelty of VR experience, providing everyone with some VR experience before the main task.

In the task instructions, we informed participants that the study is generally about crowding in public transportation. So, it is highly likely that they noticed the changes in crowding level between trips. However, based on our informal debriefings, they were not in any way aware of our hypothesis that crowding influences time perception. There is a chance that awareness of the crowding level manipulation influences one's affective rating: to rate based on how one thinks unpleasantness "should" increase by increase in crowding rather than directly experiencing it. However, we do not expect it to cause any bias in perception/reporting of trip duration. In fact, this could be a source of noise in affective ratings rather than biasing the effect of crowding on time perception or mediation of this effect by valence.

While crowding is an unpleasant phenomenon worldwide (Evans, Lepore, and Allen 2000), its perception as more or less unpleasant may depend on different demographics characteristics such as age, occupation, or culture. Nonetheless, we posit that the underlying effect of valence to dilate or contract time, would be universal. Individual differences such as the level of social anxiety or claustrophobia would then have important contributions to how crowding manifests itself on the experience of time, as Individuals with higher social phobia, by definition, experience more intense negative feelings in a closed crowded environment. Virtual reality interventions as a tool for exposure therapy under controlled conditions (Freitas et al. 2021; Krijn et al. 2004) may then be able to use subjective duration of experience as an indirect measure of intervention efficacy.

Findings of the current study can have further implications for urban design and behavior analysis. Transportation engineers use discrete choice models to analyze passenger preferences and decisions (Ben-Akiva and Bierlaire 1999; Brownstone 2001). These models typically represent the attractiveness of a public commuting trip as a function of various attributes such as travel time, cost, and crowding level (e.g. Bansal et al., 2019; Basu & Hunt, 2012; Tirachini et al., 2017). Several previous studies have proposed using perceived travel time instead of objective travel time to improve model fits (Clark 1982; Varotto et al. 2017; Yáñez, Raveau, and Ortúzar 2010). Our results suggest that considering an interaction between passenger density and perceived travel time might improve models. Further comparison of these findings with discrete choice modeling of travel preferences in hypothetical surveys has been reported elsewhere (Sadeghi et al. 2022). Results also suggest that the impact of crowding on perceived travel time can be alleviated if public vehicles target design features to make the experience of crowding less unpleasant. As we showed, crowd density itself does not regulate perceived trip duration, but it is the affective impact of crowding. Design engineering can focus on regulating subjective rather than physical factors, which may in turn have objective consequences for decreased physiological stress.

Data collection of the current experiment was conducted before the COVID-19 outbreak. During the pandemic, authorities and scientists across the world gave extensive warnings to avoid large crowds and comply with social distancing. This portrayal of the crowd as a source of disease could cause it to trigger defense systems even more intensely, leading to heightened negative feelings, and specific emotions like fear and disgust (Chapman and Anderson 2013; Curtis, Aunger, and Rabie 2004; Curtis, De Barra, and Aunger 2011; Curtis and Biran 2001). Therefore, the influence of passenger density and its subjective affective impact on perceived travel time is likely only to get stronger. The emphasized negativity of crowding during the pandemic could be even more long-term, carrying on in a post-pandemic age when the threat of the virus is alleviated, leading to decreased popularity of commuting with public transit. It will be critical for future studies to shed light on the short- and long-term effects of COVID-19 pandemic on perceptions of crowding, and its social and emotional consequences.

Declarations

Competing interests

The authors declare no known conflict of interest associated with this publication.

Data and code availability

The data and analysis code that support the findings of this paper are available at: https://github.com/saeedeh/Crowding-Time-VR

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Tables

Table 1

Mean and standard deviation of Valence and temporal bias for each crowding level

	Crowding Level				
	1	2	3	4	5
positive valence	5.15 (1.1)	5.07 (0.7)	4.61 (0.7)	3.66 (0.9)	3.27 (1.1)
negative valence	2.22 (1.3)	2.27 (1.0)	2.59 (0.7)	3.66 (1.1)	4.12 (1.4)
time perception bias	-15.61 (14.6)	-12.02 (12.8)	-11.34 (11.4)	-5.73 (21.1)	-9.71 (13.5)

Figures

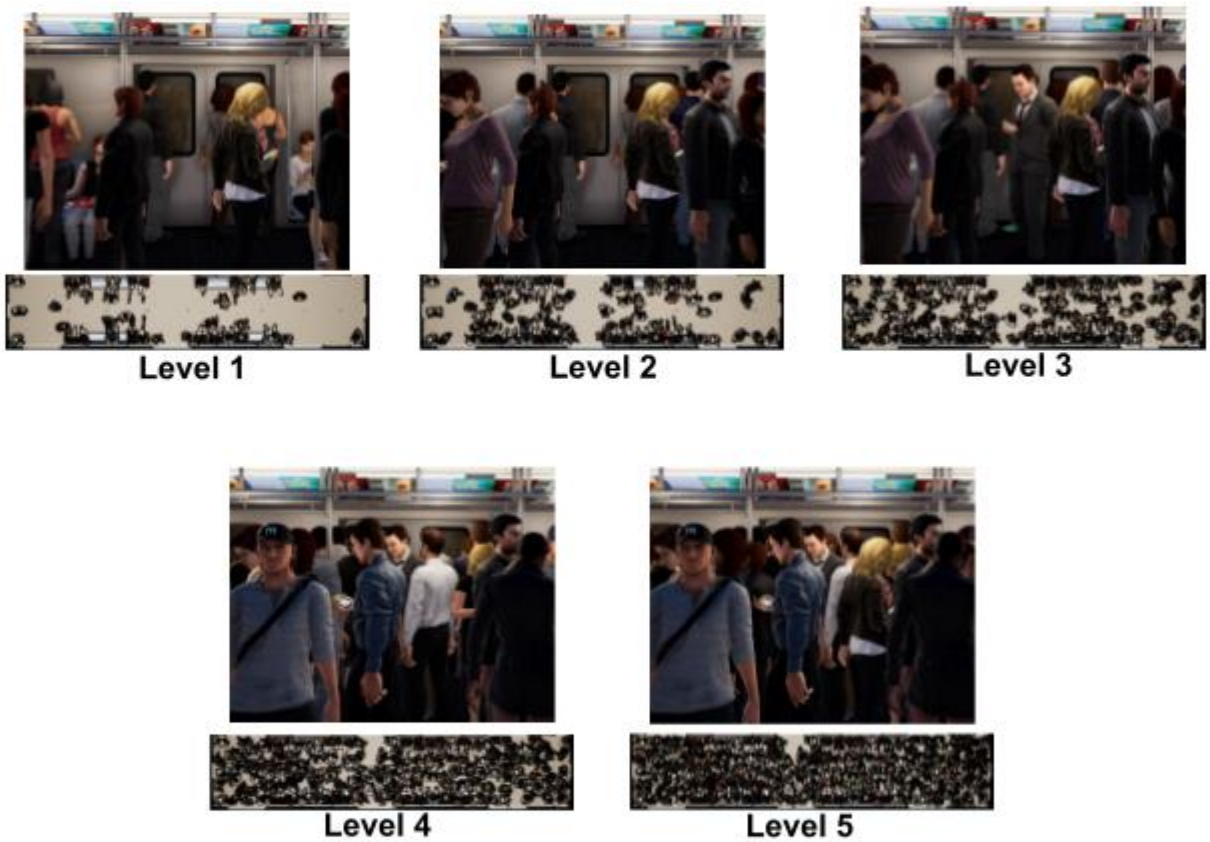

Fig. 1 Screenshot of passenger's view and cross-sectional view of the five passenger density levels in the VR environment

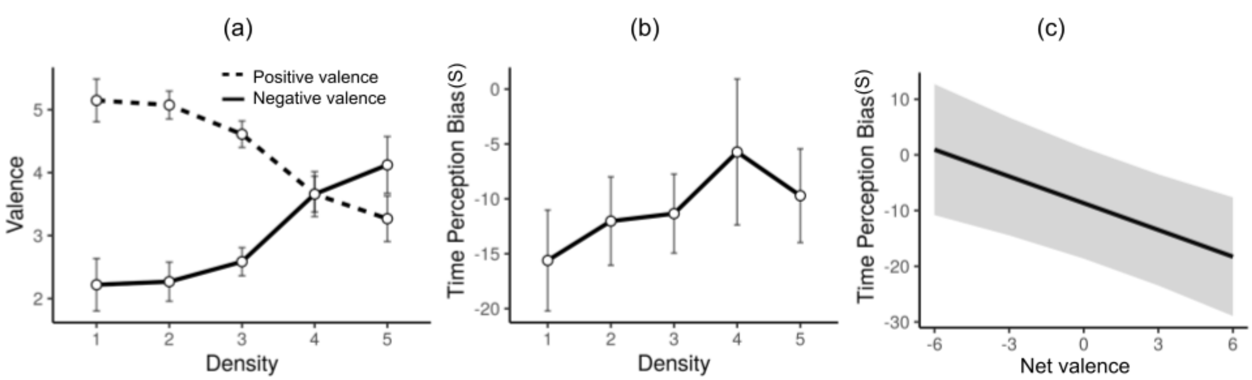

Fig. 2 a and b) The relationship between passenger density level and time perception bias (a) and positive and negative valence (b). c) Relationship between valence time perception bias. The regression line and dashed shaded 95% confidence interval are obtained from the mixed effect linear regression model (to control for between-individual variance).

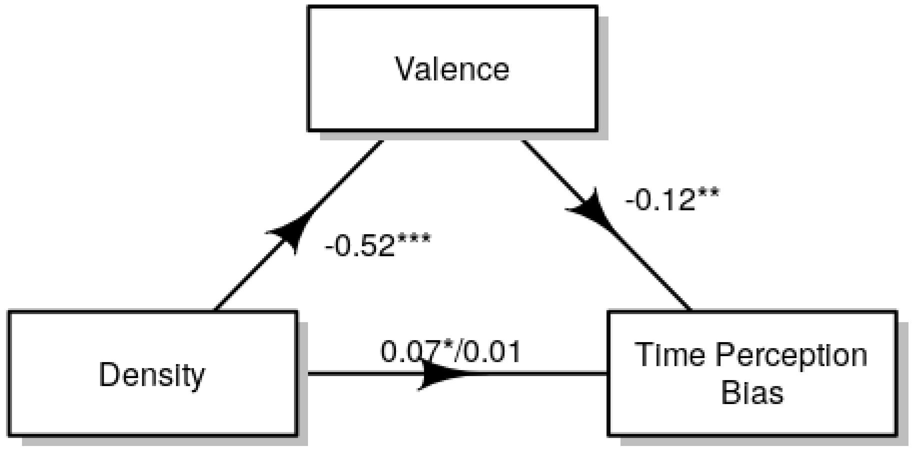

Fig. 3 Influence of density on time perception bias, direct or mediated by valence. Numbers represent standardized regression coefficients. The second number on the density-time perception path is the effect when valence is controlled. (* p<0.05, ** p<0.01, *** p<0.001)

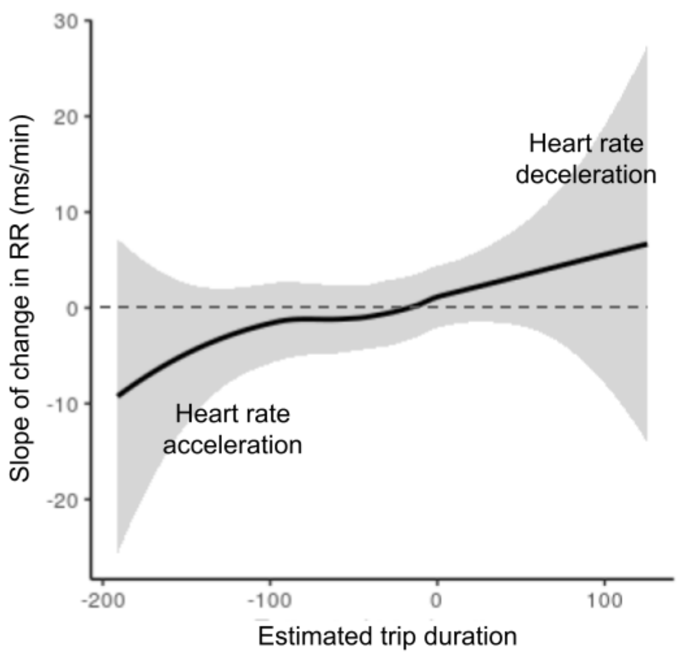

Fig. 4 Relationship between perceived travel time and slope of change in cardiac IBI during a VR trip. Perceived travel times (in seconds) are demeaned within each subject to eliminate the effect of a person's average perceived time. The curve shows the LOESS-smoothed estimate of the relationship, and the gray shade represents the 95% confidence interval.

Supplementary materials

Supplementary video. Setting of the VR task. The monitor displays the environment from the participant's perspective. Participant rested his right hand on a stand to obtain higher quality cardiac recordings. A background sound was played simulating the sound of the train.

Supplementary audio. Sample audio played during trips. The audio started with the standard NYC subway announcement saying "stand clear of the closing doors please," followed by a beep sound and sound of a subway car starting to accelerate. The subway car sound started to decelerate near the end of the trip, and it ended with another beep sound. Duration of the trip (here 70 seconds) was from the starting beep until the end beep. A similar audio-except in duration between the two beeps-was played for all trips.