Time slows down on a crowded train

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27 Abstract

28 Numerosity, complexity and affect are among factors known to dilate perceived time. While
29 such objective and subjective factors are usually tested in isolation with simple stimuli in the lab,
30 here we examined the perceived passage of time in the ecology of daily social life: crowded
31 public transit. Higher crowding level denotes a higher numerosity along with increased negative
32 affect. Accordingly, we hypothesized that crowding lengthens subjective trip duration.
33 Participants (N=41) experienced short (between 1 to 2 minutes) immersive subway trips using
34 Virtual Reality (VR). Each individual experienced multiple virtual trips with different crowding
35 levels. After each trip, they were asked to estimate the trip duration and rate its affective
36 pleasantness. Presence of one additional person per square meter of the train significantly
37 increased perceived travel time by an average of 1.8 seconds. Rather than objective factors, this
38 effect was mediated by subjective negative feelings induced by crowding. Analysis of cardiac
39 data also revealed the slope of change in heart rate during a trip as a physiological source of
40 perceived travel time, independent of the crowding level. This study is an example of bringing
41 basic psychological and physiological findings into an ecologically valid setting using VR
42 technology. Findings have broader implications for the effects of disliking social crowding on
43 our daily perceptions, which is likely more pronounced during or even after the COVID-19
44 pandemic.

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48 Introduction

49 If we consider time as one dimension of existence, then passage of each and every
50 moment is like moving forward but in time rather than space. In this analogy, we are all
51 constantly traveling in time, moving from one moment to the next. However, according to
52 Einstein's well-known theory, objective time-which is based on immutable laws of physics-can
53 dilate or contract (Einstein, 1905). The relativity of time occurs not only at the objective level
54 due to physical factors such as velocity in Einstein's theory, but it also happens in the observer's
55 subjective sense of time's passing through psychological mechanisms. Time appears to slow
56 down during an accident (Arstila, 2012). A trip from home to a shopping mall feels longer than
57 the return trip, even though they have the same objective distance and duration (van de Ven et
58 al., 2011). This later example is a situation of traveling both in time (as we always do) and space
59 (between two places), showing that a spatial trip can feel longer or shorter depending on the
60 subjective perspective. In a metaphorical restaging of Einstein's train experiment for illustration
61 of relativity, we examined a socioemotional relativity of travel time in a virtual subway car. We
62 tested the effect of density of individuals in the limited space i.e. crowding, on perceived travel
63 time of public transit commutes in an immersive Virtual Reality (VR) environment.

64 Several variables associated with an altered perceived duration of an interval include
65 objective stimulus factors such as complexity (Aubry et al., 2008; Roelofs & Zeeman, 1951;
66 Schiffman & Bobko, 1974), and numerosity (Dormal et al., 2006; Hayashi et al., 2013; Xuan et
67 al., 2007), as well as internal factors such as emotion (Droit-Volet, 2013; Droit-Volet & Meck,
68 2007; Lake, 2016; Lake et al., 2016; Schirmer, 2011). Although usually tested with less realistic
69 stimuli, these factors are closely related to a daily-life context, i.e. social crowding. Crowding is
70 an inevitable aspect of urban life with certain sensory characteristics, such as visual numerosity,

along with negative emotional influences, especially during the age of Covid-19 pandemic. Both sensory and emotional aspects of crowding could contribute to a distortion of the perceived time.

The visual aspect of crowding is the view of a higher number of individuals 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 & Verner, 2014; Xuan et al., 2007). Higher numbers of dots are perceived longer than fewer dots with the same objective duration (Dormal et al., 2006; Hayashi et al., 2013; Long & 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 & Zeeman, 1951; Schiffman & Bobko, 1974). More dynamic visual displays with more complex motion are perceived longer compared to more static ones or with simpler movements (Brown, 1931).

The role of distinct stimulus characteristics on time perception has been commonly examined with simplistic stimuli such as dots, simple geometrical shapes, or characters shown on a computer screen and usually tested with intervals shorter than a couple of seconds. It is unknown how these factors scale up to more complex real-world conditions, and durations with magnitudes of consequence for choice and behavior. Here we examine whether the effects of stimulus factors, such as numerosity and complexity shown to regulate perception of brief

duration stimuli, apply to a more complex and realistic social situation of riding a subway car with people.

Crowding is not only a different sensory 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 violated, our defense systems, which have evolved to deal with threats to physical survival, are likely to be activated (Todd & 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 et al., 2006; Kalb & Keating, 1981; Stokols, 1972). Several components of affective reactions to crowding in public transit include feeling uncomfortable, distracted, frustrated, and irritated, which have been associated with higher levels of stress and somatic symptoms such as headache, tension, and stiff muscles (N. D. M. Mahudin et al., 2012; N. M. Mahudin et al., 2011).

Emotions are connected with perception of time (Droit-Volet, 2013, 2018; Droit-Volet & Meck, 2007; Lake, 2016; Lake et al., 2016; Schirmer, 2011). In fact perception of duration is sometimes described as accumulation of 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). Observers overestimate the duration of time looking at angry faces compared to neutral faces (Droit-Volet et al., 2004). 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), like how

emotions regulate the peripheral cardiac pacemaker to alter heart rate (Cacioppo et al., 2000). However, the exact mechanisms of affective modulation of time perception are still debated (Lake et al., 2016), as is the relation between time perception and autonomic states that regulate physiological pacemakers, such as heart rate (Schwarz et al., 2013).

As reviewed above, previous works show that these physical and affective characteristics of social crowding lengthen experience of time, although tested in isolation with simple stimuli and usually in intervals of shorter than a few seconds. Here we examined the objective factors of passenger density or physical closeness to others to regulate an internal subjective factor of crowding discomfort. We hypothesized that social crowding in an ecologically valid virtual context leads to negative feelings and accordingly a lengthened perceived travel time at durations in the order of minutes. In order 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 affective ratings after each of 5 virtual trips that had 5 different crowding levels (**figure 1**). Our VR environment was sufficiently realistic, that conditions with higher levels of crowding were perceived as more emotionally negative. We hypothesized that a higher crowding level makes a trip be perceived longer, and that this effect is, at least partially, mediated by the negative feelings induced by crowding.

The homeostatic time perception theory associates temporal perception to 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 & Wittmann, 2011). We also recorded heart rate data during the experiment using a wristband pulse device. The purpose of heart rate recording was to explore the potential link between objective physiological changes and subjective travel time perception and its affective components.

Results

Each participant experienced five VR trips with five different crowd density levels (**Figure 1**; also see **supplementary video**). Net emotional valence of a trip, defined as pleasantness rating minus unpleasantness rating is represented in **Figure 2.A**, averaged for each density level across participants. As we can see, valence of an experience decreased, as a function of increase in density level ($\beta=-1.03$, $SE=0.099$, $p<0.0001$). However, arousal level, estimated by summing up the pleasantness and unpleasantness ratings was not significantly predictable from density ($\beta=2.4e-3$, $SE=0.033$, $p=0.94$).

Observers were able to assess objective differences in temporal durations, with perceived duration increasing with objective duration of train ride ($\beta=0.76$, $SE=0.14$, $p<0.0001$). We defined a measure of *time perception bias* as the actual duration of a trip subtracted from the participant's perceived duration. **Figure 2.B** represents mean bias in time perception (in seconds) for each density level. Time perception bias was on average significantly negative ($\beta=-10.88$, $SE=4.81$, $p=0.029$), indicating a tendency towards underestimation. As hypothesized, crowding level predicted a temporal bias in trip duration ($\beta=1.81$, $SE=0.74$, $p=0.016$). 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.

An observer's bias in travel time could also be predicted from the feelings about the trip (**Figure 2.C**). There was a significant effect of valence in predicting time perception bias, with more unpleasant trips (more negative valence) being perceived to be longer ($\beta=-1.60$, $SE=0.44$, $p=0.0003$).

Both density and subjective affective valence of a trip predicted the extent to which observers were biased in perceiving trip duration. Further mediation analysis was conducted to answer whether subjective affective experience mediated the relationship between crowd density and time perception bias. Results of the mediation analysis are presented in **Figure 3**. As expected, results revealed a significant mediation effect (estimate=1.55, 95% confidence interval=(0.46, 2.63), $p=2e-16$), 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 valence 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 data during trips didn't show a significant effect of the average Inter-Beat Interval (IBI) during a trip on crowding level ($\beta=0.001$, $SE=0.014$, $p=0.36$), perceived travel time ($\beta=5e-6$, $SE=1.4e-4$, $p=0.96$), or actual travel time ($\beta=-2.1e-4$, $SE=2.2e-4$, $p=0.35$). However, there was a significant overall decrease in IBI during a trip ($\beta=-5e-4$, $SE=8.7e-5$, $p<0.0001$), indicating an increase in heart rate. As shown in **Figure 4**, a larger slope of this IBI change, i.e., more deceleration 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 subjective valence of the trip ($\beta=2.8e-8$, $SE=2.1e-5$, $p=0.90$) and its 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 minutes 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 an internal sense 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 negative feelings. This result is in agreement with previous evidence that negative emotions lengthen perceived duration (Droit-Volet, 2013; Droit-Volet et al., 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. Positive experiences were associated with a greater contraction of time relative to objective durations. As such, time flew by, i.e., greater contraction relative to objective duration, the more pleasant the trip.

Independently of crowding and valence, analysis of the cardiac data showed a significant decrease in IBI (i.e. increase in heart rate) during a trip, suggestive of sympathetic arousal and stress (Kirschbaum et al., 1993). A positive rate of change in IBI, i.e. less increase or more decrease in heart rate explained lengthened 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 & 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 attentional rather than affective processes. This finding is aligned with an ample amount of evidence that increased attention lengthens subjective time (Grondin, 2010).

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. VR is an excellent tool for creating social stimuli that are more controlled than real stimuli, are replicable, and may be impractical or too expensive to attain in the real-world (Fox et al., 2009). Increased density of virtual avatars caused an increase in negative feelings during the trip, validating that they were sufficiently realistic to induce the negative feelings associated with overcrowding in real-world commuting trips (Cheng, 2010; Cox et al., 2006; Kalb & Keating, 1981; N. D. M. Mahudin et al., 2012; N. M. Mahudin et al., 2011; Stokols, 1972).

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 a real social setting, crowding has other components such as smell and noise that are beyond the visual closeness to strangers (Haywood et al., 2017). Here, however, we only manipulated the visual aspect of crowding in different passenger density levels. 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. Virtual avatars were also visually distinguishable from real humans. Participants did not actually intend to travel to a destination, and were only asked to imagine so. 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 of this study was the undergraduate demographics of our sample. While crowding is an unpleasant phenomenon worldwide (Evans et al., 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.

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 & 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 the objective travel time to improve model fits (Clark, 1982; Varotto et al., 2017; Yáñez et al.,

2010). Our results suggest an interaction between passenger density and perceived travel time. Therefore, considering this interaction term in these choice models might be beneficial to obtain a better fit to humans' behavior. Furthermore, our results 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 rather 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 all 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 (Chapman & Anderson, 2013; Curtis et al., 2004, 2011; Curtis & 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. 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 consequences on use of public transit.

Methods

272 Participants

273 Forty-two individuals were recruited at the Ithaca campus of Cornell University to
274 participate in the experiment. Student volunteers received extra course credit as compensation
275 for their participation. One participant didn't finish the experiment due to feeling nauseous. All
276 other individuals were included in further analysis (N=41). Participants were between 19 and 51
277 years of age ($M=22.6$, $sd=5.5$), and consisted of 19 females. All participants gave informed
278 consent in accordance with the Institutional Review Board at Cornell University. Data collection
279 was performed prior to the COVID-19 pandemic in fall and winter of 2018.

280

281 VR environment

282 The VR environment was developed to simulate the inside of a subway car, including
283 moving avatars of passengers (**Supplementary video S1**). The dimensions and the interior of the
284 subway car were created to represent the New York City subway car R160 model ($13.61m \times$
285 $2.59m$, $35.25m^2$) currently in service. Five conditions were used in the experiment to present five
286 different levels of passenger density.

287 The number of passengers in the car in each condition was determined to have one, two,
288 three, four, and five passengers per square meter. For example, the lowest density condition was
289 created with one passenger per square meter, i.e., 35 passengers in $35 m^2$, and the highest density
290 condition was with five passengers per square meter, i.e., 175 in $35m^2$. Seating and standing
291 passengers were placed with random distributions to look natural while keeping the total number
292 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 $2,160 \times 1,200$ ($1,080 \times 1,200$ 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.

Figure 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. Sounds were identical for all crowding conditions.

Procedure

The experiment included a number of virtual trips on a subway car. For all trips, the participant 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 (**supplementary audio S1**). 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**). 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

315 subway car (5 density levels). Participants were informed that the trip duration is the time
316 between the first bell and the second bell ringing sounds.

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

325 VR task

326 The VR task included experiencing 5 trips with all 5 different passenger density levels in
327 a randomized order, each having a randomly selected duration among 60, 70, or 80 seconds (with
328 equal probability). After each trip, participants were asked to take off the headset and sit at a
329 computer to answer the questions about their experience. These questions included the
330 following:

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

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

335 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), to allow for assessment of mixed feelings and while also allowing derivation of arousal levels (Kron et al., 2013, 2015). Magnitude and direction of net valence was defined as pleasantness rating (question 1) minus unpleasantness rating (question 2). Arousal, which is defined by the overall intensity of one's affective experience, was estimated by summing pleasantness and unpleasantness ratings (Kron et al., 2013).

Physiological recording and analysis

Cardiac data was 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 S1**) 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 arousal 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.

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 valence 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 *gaml* 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.

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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Figures

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

Figure 2. A and B) The relationship between passenger density level and time perception bias (A) and valence (B). Error bars represent within-participant standard errors estimated using the method outlined in (Morey, 2008). **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).

Figure 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. (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$)

Figure 4. Relationship between perceived travel time and slope of change in cardiac IBI during a VR trip. Perceived travel times 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 grey shade represents the 95% confidence interval.

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