A Virtual Reality Experiment to Investigate Optimum High-Density Apartment Parameters

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Abstract: The current study uses Virtual Reality (VR) to experimentally investigate how room shape and volume affect perception of space and perceived size to identify optimal design for densified urban apartments. Optimal parameters are defined as (1) room shape that produces the largest increase in perceived space with the smallest increase of objective space (2) rooms that produce high perceived spaciousness and livability ratings. Participants experienced a series of virtual rooms of different shapes and volumes, and were asked to scale a cubed reference room to match the size of the target room. While room shape determined the accuracy of the spatial perception it is suggested that the optimum parameters of ceiling height and room width affect perceived spaciousness and liveability. Defining optimum parameters of room height, width and shape are foundational to providing strategies in apartment design to produce optimum perceived spaciousness and liveability. This research aims to firstly, develop a new method for studying optimal architectural design parameters, and secondly study the relationship between perceived space, shape and volume to form optimum parameters. Future research can then build on these parameters and introduce more complex parameters to produce defensible architectural strategies for optimizing high-density design.

Keywords: Occupant wellbeing, virtual reality, perception of space, densification.

1. Introduction

1.1. Densification

Densification is an inevitable consequence of growing city populations. Projections estimate that by 2050 75% of the world’s population will be living in cities compared to 50% in 2007, and 10% in 1900 (Nations, 2014). Currently 24% of urban density around the world is between 10,000 – 100,000 people per square kilometre. In 1939 while urbanisation was increasing in Berlin the population density decreased from 29,000 to 5,600 people per square kilometre. The population increased by three million people and 800 square kilometres as the city expanded (Bosselmann, 2012). However, once cities reach a certain size a rate of expansion is no longer sustainable or possible resulting in an increased rate of population density. The 50% urbanisation increase from the 1900’s to the present has resulted in the top 26 largest urban
areas in the world having a population density which is increasing more rapidly than expansion (Cox, 2015). The reduced size of living environments is a consequence of increased population density. Densified living environments can result in discomfort and dissatisfaction, especially in high density housing (Wong et al., 2009). Densification can cause issues in living situations affecting occupant wellbeing which needs to be addressed. Simply creating larger high density spaces is not a viable solution as the available space decreases as population density increases. “It is simply impossible to increase the amount of space available to individuals incarcerated in cities” (Worchel, 1978, p. 28). By taking a scientific approach we can establish the optimum measures to improve spatial responses in high density design. A defensible set of optimal design parameters which challenges the issue of densification are required. These parameters are a crucial development to providing high density architecture which optimise liveability, spaciousness and perceived size.

1.2. Overcrowded Stress

By creating smaller living size conditions there is a potential to affect the overall wellbeing and comfort of the occupants (Kopec, 2006). This can lead to living dissatisfaction and discomfort and in serious cases depression and violence (Solari and Mare, 2012). The most common effect of densification is overcrowded stress. Overcrowding has three main manifestations stimulus overload, behavioural constraint, and ecological orientations, each of which have either a social or physical evoker (Stokols et al., 1973). Densification in an apartment context largely contributes to overcrowded stress with stimulus overload from physical stressors, which the built environment effects. Evans et al. (2003), while discussing the factors of overcrowded stress suggests that reducing it is essential for high density housing which can more positively affect occupant wellbeing. An approach which can increase the subjective or psychological space with minimal objective increase will help to minimise the effects of densification. An increase in psychological space has the potential to reduce the negative psychological effects of overcrowding stress. During an investigation of crowding and density Stokols (1976) suggests that “perceived crowding might be reduced through cognitive or perceptual strategies designed to expand psychological space” (p.69). This indicates that a designed space could alter an individual’s perception of space and density resulting in an increase of wellbeing and comfort. Baldassare (1979) found that subjective ratings of perceived crowding correlated strongly to the prediction of living discomfort. People were able to determine the environmental quality of a space through perceived density. This suggests that architecturally designed rooms can improve the wellbeing and comfort of occupants in densified environments by altering the perception of space, as supported by Cohen et al. (2013). He discuss the effects of ‘crowding’ to be a largely subjective response to densification. Booth and Cowell (1976) also tested objective and subjective crowding relationships through survey responses. Thirty-three relationships between density and stress were measured. Twenty-one were of subjective measures of crowding, whereas twelve were of objective measures. If perceived density is largely influenced by subjective measures it would suggest that perceived density can be changed with minimal change to the objective measures.

1.3. Perception of Space

People perceive the world around them uniquely on an individual level, but there are fundamental laws that define how people experience the physical environment (Evans and McCoy, 1998). This leads to question how the laws of perceived space can be tested to understand perceived size and subsequently alter perceived space. Hayward and Franklin (1974) discuss the relationship between the built environment to perceived openness or enclosure. They conclude that a lower height of back wall (H)
divided by the distance to wall (D) has an increased openness. “Impression of openness-enclosure of architectural space is determined by size-distance relations regardless of actual scale of space. As the value of the H/D ratio increased, perceived enclosure also increased” (p. 39). The experiment conducted in this research was highly abstracted in practice and does not serve as an adequate equation to challenge densification. Rather this research acts as an insight into the foundational information into perception of space. Additionally as precedent, forming studies involving perception of space. Sadalla and Oxley (1984) also explored this concept with a series of experiments. From these Sadalla and Oxley concluded that ratios of a rectangular room greatly influence the perceived size. The understanding of perception within a rectangular form concluded that a greater ratio of length/width implied a larger perceived space. In both of these experiments the fundamentals of perception of space were tested in regular cubic and rectangular form. However, this leaves a gap in understanding around perception of space in irregular form. Typical apartment design is not of regular form so to improve our understanding of perceived density an exploration of perceived space including irregular form is necessary.

1.4. Conservation of Space

In the current study, subjects were asked to scale a cube to match the volume of another shape; a conservation of space task. Conservation refers to the ability to determine that a certain quantity will remain the same despite adjustment of the apparent size or shape (Siegler et al., 2003). Piaget (1976) tested children’s perceptions of space by testing the concept of conservation by tipping the same amount of liquid into two vessels of the same volume yet different shapes. The exercise illustrated that children would rate the tallest of the vessels to be larger when asked which container had the most liquid. “Children’s perceptions in this stage of development are generally restricted to one aspect or dimension of an object at the expense of the other aspects” (Ojose, 2008, p. 27). This ability develops around late childhood (Piaget, 1976). The proposed experiment will test the ability to apply conservation of space in more complex scenarios to investigate which aspects or dimensions of rooms produce larger perceived spaces. The method of experimentation with VR allows an in depth evaluation of architectural understanding, architectural qualities, and observation of user experience and perception of space. The medium of VR grants a controlled environment to conduct research enhancing perceptual understanding of 3D volumes (Schnabel and Kvan, 2003). The ability to experience the rooms in a first person perspective means a measure of perception of space can be observed and recorded. This would not be possible with another medium with the same level of immersion and reliability. The results of the experiment will suggest how apartments could be designed to feel more spacious and reduce the perceived density of the space. We hypothesise that room shape will have a relationship towards the perceived size of a space, resulting in a positive or negative association (perceived larger or smaller) at a constant volume. This would result in a room shape having a larger psychological space increase than the objective space increase while increasing perceived livability and spaciousness. We also predict that it will be harder for the participant to match volumes as room size increases.

2. Method

2.1. Participants

For the VR experiment 30 subjects participated in the study with a demographic ranging from 20 to 50 years of age with an average of 26.7 years old. The sample of 33.3% females over represents males. The sample size is derived from the application ‘Piface’ power and sample size calculator to achieve 80%
power, or 95% confidence Intervals with an accuracy of 5 or 10%. Subjects were selected if they had not had education in the field of design. Conservation of space is a developed ability which can only improve with education (Judd, 1940). This informed the decision to exclude any participants with architectural education who may have a trained eye or advantage in the experiment.

2.2. Materials

2.2.1. Equipment and Software

The VR equipment used was a HTC Vive, 2160 x 1200, 90Hz refresh rate, with a 110 degrees field of view, and a tracking area of 15x15 feet. Alienware Aurora R5 Processor connected the VR equipment and programs with an Intel(R) Core(TM) i7-6700, CPU @ 3.40GHz, 3401 Mhz, 4 Core(s) 8 Logical Processor(s), RAM 16.0 GB, CPU Intel Core i7 (6th Gen) 6700 / 3.4 GHz Type Core i7, and NVIDIA GeForce GTX 1070. Excel 2013 and IBM SPSS Statistics 24 were used during the data analysis and to produce graphs. Steam VR and Unity 5.5.1 were used to run the experiment.

![Figure 5: VR set up and equipment](image1)

![Figure 2: In-experiment VR view](image2)

2.2.2. Rooms and Set up

Perceived illuminations affect perception of space so well defined edges are needed to accurately perceive a room (Gilchrist, 1979). A grey scale allowed the wall definitions to stand out more than the white, allowing for a clear understanding of the shape. Without a clear definition of the rooms boundaries the participants would struggle to interpret the space. Lighting and colour also has an effect on perception of space (Manav and Yener, 1999). A single lighting system with constant light and colour was chosen to create a consistent light dispersal over each Room. Room sequence was randomised across all participants to remove any learning trends. Words were programmed to appear at the top of the controller which stated which Room they were in with minimal visual interference. This was to reduce any confusion the participant may experience which could affect the results of the study by putting them off task. Participants were also asked an exit question of whether they had experienced any motion sickness of which zero were reported.
Perception of space is a subjective response which requires a within subject study process to effectively remove subject to subject variation (Seltman, 2012). The dependent variables are the shaped rooms. The rooms were selected for basic shapes which allow a wide range of investigation and of which can be associated with the most typical apartment proportions and shapes. The independent variables are the sizes of a Scalable Room which the subjects manipulate. The scalable Room will be referred to as the Scale Room. The Scale room is a 50m³ cubed room which is scaled at the end of each Room sequence to match the Room’s volume. The Rooms had a baseline of 50 m³, same as the Scale Room before manipulation. However, for each participant the Rooms randomize in size within a range of ±50% (25-75m³). This removes a size effect bias which could affect the data output. After the matching is complete the Scale Room reverts back to 50m³ to allow for a consistent starting point for each participant. The in experiment questions were chosen with the anchor points of enclosed – neutral – open, and strong no – neutral _ strong yes, to understand the perceived spatial qualities of the rooms (table 1).

Table 1: Experiment questions

<table>
<thead>
<tr>
<th>Pre-experiment questions:</th>
<th>Post Room scaling questions:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) What is an estimate of the size of your current living room in cubic meters?</td>
<td>1) On a scale to 1 (Strong No) – 5 (Neutral) - 10 (Strong Yes) rate if you would like to use Room #/ Scale room as a living room.</td>
</tr>
<tr>
<td>2) How many people use the living room typically?</td>
<td>2) On a scale to 1 (Enclosed) – 5 (Neutral) - 10 (Open) rate the spaciousness of Room #/ Scale room?</td>
</tr>
<tr>
<td>3) How would you rate the spaciousness of your current living room? 1 (Enclosed) - 5 (Neutral) - 10 (Open)</td>
<td></td>
</tr>
<tr>
<td>4) How would you rate the comfort of your current living room? 1 (Uncomfortable) - 5 (Neutral) - 10 (Comfortable)</td>
<td></td>
</tr>
<tr>
<td>5) How many hours a week do you play video games?</td>
<td></td>
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<tr>
<td>6) Have you used VR before?</td>
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</tbody>
</table>

2.3. Procedure

Participants were individually bought into the VR laboratory and asked to fill in pre experiment questions, see table 1, and subject information. Once the experiment process was explained the subjects were introduced to the Scale Room. The experiment started with a ‘size test’ for each participant to determine the individual’s ability to match volumes. Three cubed rooms, no shape change, with a randomly selected order were set for the size test with sizes of 30m³, 40m³ and 60m³. The participant had 30 seconds to explore a Room before going back to the Scale Room to best match the Room’s volume size. The participants were given a 10 second warning before the end of the time limit. When the participant was confident (or as close as) that the volumes are matched they were given another the 30 seconds in the Room after which they were allowed to make any alterations. This process illustrated the individual’s and the group’s ability to match same shape volumes with reasonable accuracy.

For the next part of the study the subjects followed the same process with a series of different shaped rooms (Figure 3). The subjects had 30 seconds in the Room before returning to the Scale Room to match the volume. Once complete the participants were asked to verbally complete questions describing their perception of both the Scale Rooms and Shaped Room in terms of perceived liveability and spaciousness.
Once the questions were completed the participant repeated the process with the subsequent Room’s, as seen in Figure 3.

![Room Shapes](image)

**Figure 3: Virtual room shapes**

### 2.4. Analysis Strategy

The size (m³) of both the Rooms and the Scale room (after scaling) was recorded after each sequence. This data showed the perceived size accuracy of a room which illustrated a larger or small perceived space. For example a participant scaled the Scale Room to 50m³ where the Room experienced was 40m³. This illustrates that the participant perceived the Room to be +25% or 10m³ larger than its objective size. A positive percentage or size indicates that the volume was perceived larger than the objective size. Likewise a negative result indicates a smaller perceived size. At the end of each Room sequence the subjects were asked to rate the livability and spaciousness of both the Room and the Scale room. Questions on livability and spaciousness were asked to firstly, establish how spaciousness and liveability are effected by room shape and volume. Secondly, to establish whether they had a relationship to the accuracy in perceived size of a room, of which none was established. The data produced were numbers ranging from 1-10 with specific anchor points, see table 1.

### 3. Results

The experiment variables are the dependent variable of Room shape and volume, and the independent variable of the Scale Room volume after manipulation by the subject.

### 3.1. Perception of Space

There is a clear relationship between perceived size accuracy and volume shape (Figure 4). Participants almost always overestimate the size of the room, though the effect was stronger in some rooms. Room D has the largest perceived space and Room A the smallest perceived space with the same objective size (figure 4 and 5). As expected the size tests (Rooms 1-3) show minimal perceived size variance as room shape was constant. The randomization of the rooms had equal distributions around 50m³ (figure 5). There is a slight decrease in average Room size in Room B however there is an insignificant difference.

Average room width follows a moderate correlation of $r = 0.545$ (Figure 6). This suggests a relationship between the two variables but suggests the possibility of other contributing factors. There is also a weak correlation between ceiling height and perceived size accuracy where $r = 0.283$. This suggests that multiple contributing factors influence the perceived size accuracy of a room.

As room size increases volume matching accuracy decreases (figure 8). Perceived Liveability and spaciousness is strongly correlated to perceived liveability, $r = 0.872$ (Figure 9).
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Figure 4: Accuracy of perceived space over each Room. A larger perceived space is an overestimation of the room size.

Figure 5: Average room sizes during the experiment, showing no systematic bias.

Figure 6: Moderate positive correlation between average room width and perceived spaciousness, $r = 0.545$.

Figure 7: Weak positive correlation between ceiling height and perceived size accuracy, $r = 0.283$.

Figure 8: As room size increases the accuracy of volume matching decreases.

Figure 9: Positive correlation between perceived spaciousness and liveability $r = 0.872$. 
As room size increases the optimum room shape changes. This suggests that multiple parameters determine an optimum room at a given size. This differs from our original hypothesis that perceived liveability and spaciousness would have a positive relationship to perceived size. Room G is the ideal room in terms of perceived spaciousness and livability at small volumes (20-40m³) and Room B at the large volume (60-80m³). However, around 50 cubic meters (40-60m³) both perceived spaciousness and liveability ratings cluster with similar results. In all room shape examples perceived spaciousness has a positive relationship to room size. However, room shape determined the rate of increase suggesting that optimum solutions can be achieved through optimising room shape and size.

![Graphs showing the relationship between room size and perceived spaciousness.]

4. Discussion

This study used VR to measure the effect of room shape and volume on perceived space. Overall, room spaciousness was correlated with average width, suggesting that people base judgements of spaciousness on room width. These results support research by Hayward and Franklin (1974), who found that room depth and perceived openness had a positive correlation. However, perceived room size was only weakly correlated with ceiling height, suggesting that other parameters could be contributing also. The correlation, though weak, is supportive of research by Piaget (1976), who found that conservation of space was generally restricted to one dimension of an object which was typically height. Alternatively, the increased ceiling height simply increases the difficulty to accurately perceive a room’s size. This interpretation is supported by Figure 8 showing that as room size increases perceived room size accuracy decreases. Research by Sadalla and Oxley (1984), contrary to the results suggesting ceiling height influences perceived size, state that a greater length over width ratio forms a larger perceived space. Room D, which was the largest perceived space, had the smallest length/width ratio. The method used could influence the results produced by Sadalla and Oxley (1984) through a purely two dimensional investigation using perspective lines to gage perceived size. This possibly influenced the results leading to room height as an insignificant contributing factor. Their process differs from a VR experiment in that the perceived space is three dimensional and participants have the opportunity to look up and around.
A negative relationship between perceived size accuracy and actual room size suggests that psychological space is more impactful at smaller volumes. However, as room size increases accuracy decreases (figure 8). This would indicate that as the room increases in size the data associated in perceived size becomes less reliable. Therefore any trends taken from Figure 12 would need to be confirmed by further research. Though Room D met requirement (1) the room did not meet requirement (2) suggesting that an optimum room needs to utilise multiple parameters to meet both requirements. Due to multiple parameters contributing towards forming an ideal room further research is needed to investigate the optimum relationships between them. It is suggested that there are thresholds in parameters which cause significant change in perceived space. It is essential to establish parameter thresholds which vary responses of perceived livability, spacious and size as larger rates. This has been suggested in Room D which, compared to the other rooms, had a comparatively lower average room width resulting in a significantly reduced perceived spaciousness and livability. Likewise, in Room D with comparatively larger ceiling height produced a significantly larger perceived size. Establishing the crucial thresholds and understanding how they relate is fundamental to developing accurate and useful optimum design parameters. Currently the research illustrates that the height and width of a room influence perceived liveability, spacious and size. With this knowledge the perceived space in high density architecture can be optimised. However, due to the abstract nature of the virtual rooms further studies are needed to determine any additional parameters in more complex environments.

5. Conclusion

Overall, the method achieved the desired output of basic optimum design parameters. The data suggests that ceiling height is a contributing parameter to perceived room size accuracy and that average room width contributes to perceived spaciousness ratings. However, perceived size and perceived spaciousness are attributed to different parameters and did not directly correlate. Further research is required to establish the parameter relationships to form optimum room requirements (1) and (2). This research acts as a foundation for future research which will expand and refine parameters and their relationships to produce optimum design strategies. A subsequent experiment would investigate what proportions of a room shape produces the optimum perceived room increase and optimum perceived spaciousness and livability. High density design can be optimized with this method to find the optimum efficiency of a volume. This research produces foundational parameters of height and width to form architectural strategies which could optimize spatial design. Further research would refine the parameters and method to form a full optimization of high density architecture.

References

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