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Lived space and geometric space: Comparing people's perceptions of spatial enclosure and exposure with metric room properties and isovist measures

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Past research in spatial psychology has demonstrated that some environmental properties can positively influence human emotions. While architectural designers have adopted these findings to argue for the positive psychological impact of specific spatial dimensions, there is limited evidence that people can intuitively assess the most basic properties of an interior. Furthermore, the computational-mathematical methods used to examine interior spatio-visual properties have only rarely been compared to human perceptions. Indeed, there is no evidence that two of the most basic spatial feelings – enclosure and exposure – correlate to any of the metric or isovist-based properties of space. In response, this paper presents the results of a study involving 159 participants who assessed 24 perspective views of virtual interiors for feelings of enclosure and exposure. These results are compared with the metric properties and isovist measures of these interiors to examine if human perceptions of a simple space are accurate and possess any direct correlation with isovist measures.

Keywords: design assessment; environmental preference; interior space; isovist analysis; openness; Prospect-refuge theory

Introduction

There are two broad, philosophical models of spatial understanding in use in architectural theory and history (Giedion 1966, Baird 1995, Baker 1995). The first model, *lived space*, is the space of emotional perception, it is defined by sensory information and it is at the core of phenomenological reasoning (Dovey 1993). Lived space is necessarily subjective and emotional, but it also potentially offers a logical and informed interpretation of an environment. The second model, *geometric space*, is space as it is measured in absolute terms, using metrics that are universal and repeatable (Dovey 1993). Geometric thinking and reasoning are concerned with the underlying, physical ontology of space. This second type of thinking is central to scientific paradigms in architecture and to computational and mathematical models of spatial analysis. However, while both of these models of spatial understanding are currently used in architectural research, it cannot be assumed that lived space and geometric space are necessarily related. For example, philosophers Deleuze and Guattari (1987) differentiate lived space (*smooth space*) from

geometric space (*striated space*) arguing that the two are opposing conditions, the former being associated with direct physical and phenomenological engagement, whereas the latter is distant, hierarchical and controlling. It has also been repeatedly observed that there is a disjunction between the way people perceive, memorise and understand space and the actual physical properties of space. For example, while a landmark in an urban environment may dominate the identity of that space, smaller objects within that environment can shape perceptions about the properties of the space (Lynch 1960). Nevertheless, many architectural applications of the results of environmental preference research assume that people are sensitive to metric properties and that perceptual responses to a space can be linked to its actual geometric properties (Lidwell, Holden, and Butler 2003; Kellert 2005; Montello 2007; Augustin 2009; Lippmann 2010). Two spatial properties in particular – enclosure and exposure – are the centre of several major applications of behavioural research in design, which are founded on such assumptions.

It has been argued that an environment which offers some sense of enclosure, while still allowing a degree of visual engagement with adjacent environments, is best able to satisfy basic human emotional needs (Appleton 1975; Kaplan and Kaplan 1982; Scott 1993a). In contrast, a strong or overwhelming sense of exposure or enclosure allegedly leads to feelings of anxiety, including, in some cases, agoraphobia and claustrophobia (Carter 2002; Lidwell, Holden, and Butler 2003). Furthermore, in an urban context, visual privacy can be even more critical to providing a comfortable living environment (Shach Pinsky, Fisher-Gewirtzman, and Burt 2007; Fisher-Gewirtzman 2016). Such arguments imply that lived space and geometric space are connected, or put more simply, that peoples' experience of space conforms with the actual room geometry. However, while a considerable volume of evidence has been collected about the way people respond to enclosure and exposure (Dosen and Ostwald 2016), relatively little is available about the relationship between the lived and geometric attributes of environments. This situation is the catalyst for the present paper which asks two related questions. First, what is the relationship between human perceptions of enclosure and exposure, and the geometrical attributes of environments? Second, which computational measures display a high correlation with human perceptions?

The first of the two research questions is inspired by the assumptions found in various architectural applications of behavioural and perceptual research. Multiple different approaches to environmental preference theory – including prospect-refuge theory (Appleton 1975), information theory (Kaplan and Kaplan 1989) and arousal theory (Berlyne 1951) – suggest that distinct levels of enclosure and exposure will result in positive emotional responses from people and these conditions can, moreover, be replicated in architecture (Hildebrand 1991, 1999). The catalyst for the second question is found in analytical research into these issues using computational and mathematical means (Franz, von der Heyde, and Bühlhoff 2003, 2004; Wiener and Franz 2005; Dawes and Ostwald 2014a, 2014b). Such research identifies multiple ways in which the selected geometric properties of a space can be compared with, or interpreted in the context of, the lived properties of the space. Despite the value of such examples, there is no evidence that the most basic spatial perceptions – enclosure and exposure – can be measured using metric properties or the most common computational method, isovist properties.

This paper investigates the relationship between perceptions of enclosure and exposure and geometric measures of the same space. Specifically, it compares the results of a survey of 159 participants, who assessed 24 perspective views of virtual interiors for their feelings of enclosure and exposure, with metric and isovist measures for the same 24 interiors. Through a statistical analysis the paper determines whether, for a simple room, people are able to accurately differentiate levels of enclosure (related to a varying degree of refuge in a room) and exposure (which is related to a varying degree of openness and prospect in a room), and which isovist and metric measures most closely correlate to perceptual responses.

For the purposed of this paper, a sense of enclosure is defined as a feeling of being surrounded, concealed, hidden, or protected by a space. Exposure is defined as a feeling of being open or exhibited. The former sense is a factor of a reduced visual connection to the exterior, and the latter of an increased visual connection. Thus, in the literature, the two tend to be treated as reciprocal conditions (the greater the exposure the less the enclosure), even though this has not been empirically investigated.

This paper is structured in five parts. Following this introduction is a brief background to isovist analysis and how it relates to spatial or environmental preference theory. Thereafter the methods used to gather and compare data are described, along with participant demographic information. The results, first for enclosure and then for exposure, are then presented and compared in the following two sections. The results are grouped by (1) perceptual responses, (2) perceptions sorted by demographic factors, (3) actual room properties, and (4) isovist properties. Finally, the implications of the results are discussed and the two research questions posed previously are revisited.

There are several practical limitations to the approach taken in this paper. First, the spaces used as stimuli for the tests are small and relatively simple. This is to reduce the impact of distractions and confounding factors on the perceptual results. However, it also limits the usefulness of some isovist measures. Second, despite recent developments in three-dimensional visibility analysis (Yang, Putra, and Li 2007; Morello and Ratti 2009; Bhatia, Chalup, and Ostwald 2013), most isovist studies investigate the visual experience of space only in two dimensions. In this paper two-dimensional measures are used for the correlation analysis, although they are examined in both plan and section. Third, only static stimuli are used for the survey, which might limit the experiential assessment of a three-dimensional space. Fourth, the number of participants is not equally divided across all demographic groups and so detailed conclusions or inferences cannot be drawn about all of the sub-groups who participated. Finally, this paper is only concerned with the properties of fixed isovist viewpoints, not isovist fields or paths. The extent of its analysis of isovists is also limited to their potential correlation with human perceptions.

Background

Over the last few decades, a growing number of studies have tested the relevance of various theories derived from spatial psychology to design (Scott 1993a, 1993b; Stamps 2008a, 2008b). The theories that have been tested have typically identified various spatial properties – including openness, enclosure, mystery and complexity – which have been linked to feelings of emotional

wellbeing (Berlyne 1951; Appleton 1975; Kaplan and Kaplan 1989; Hildebrand 1991, 1999). While the results of these have ranged across the spectrum from positive to negative (with many of the most compelling falling into the middle range), they nevertheless signal a serious interest in identifying and examining precise spatial and perceptual properties in architecture (Dosen and Ostwald 2016).

In parallel, with the rise of interest in testing environmental preference theory in architecture, an alternative tradition has arisen which tests these spatial properties mathematically or computationally. For example, past research has used isovist polygons and visibility graphs (derived from isovists) to examine the spatio-visual properties of environments (Benedikt 1979; Batty 2001; Turner et al. 2001; Christenson 2010). An isovist is “the set of all points visible from a given vantage point in space” (Benedikt 1979, 47) (Figure 1). Isovists change their shape and size depending on the chosen observation point within an environment, which allows them to reveal “location-specific patterns of visibility” (Benedikt 1979, 48). In an architectural context they allow for the “interrelation of space, light, and visibility” to be measured (Benedikt 1979, 48).

Figure 1

The simplest depiction of an isovist is in form of a view-shed polygon alongside with a description of its properties and their relation to spatial attributes (Hanson 1998). A basic view-shed polygon can be produced by tracing lines from a chosen observation point onto a floor plan of a building towards its surface vertices. Vertices are, for example, corners of a room or edges of openings, along which the line would be extended towards the surface of an adjacent space. Such extended vertex lines are called *occluding radials*.

Isovist analysis offers a method for comparing the mathematical properties of different views which can also be categorised in terms of distinct spatial qualities. Significantly, past research has selectively used isovist measures in the context of examining perceptual responses to space (Conroy 2001; Franz, von der Heyde, and Bühlhoff 2003, 2004; Wiener and Franz 2005).

A small number of previous studies have also sought to test how lived and geometric space relate to each other, by examining varying spatial dimensions and their impact on perceptual responses (Franz, von der Heyde, and Bühlhoff 2003, 2004; Wiener and Franz 2005; Stamps 2005). However, many of these studies rely on a small number of participants and stimuli or include additional confounding elements. For example, some studies only indirectly examine participant's perceptions by testing their ability to determine the most hidden area in a space (an indication of enclosure) or the best place for overlooking a space (exposure). Furthermore, none of the past studies examined the environmental origin of participants (the area where they grew up or lived during past years), a factor which potentially influences perceptual responses. Some researchers suggest that past experiences in similar spaces can have a positive or negative impact on perceptions of a new environment (Ellard 2009, Tuan 2013). Nevertheless, as a result of this past studies, several isovist properties have been independently linked to spatial qualities including potential or indirect perceptions of openness and enclosure (Franz, von der Heyde, and Bühlhoff 2003, 2004; Wiener and Franz 2005; Dawes and Ostwald 2013; Dosen, Ostwald and Dawes 2013). In particular, 27 isovist measures have been linked to various perceptual properties in past research (Benedikt 1979, Conroy 2001, Stamps 2005). In their meta-analysis of the mathematical and logical basis for these measures, Dawes and Ostwald (2013) identify several which would appear to be useful for measuring enclosure and exposure. Six isovist measures identified in this past research, are tested in the present paper to see if they correlate to perceptual responses to space.

Method

The method adopted in this paper combines an empirical survey with a mathematical and computational approach (isovist analysis) to test the relationship between perceptual responses (*lived space*) and actual properties of virtual interiors (geometric space). In the online-survey, 159 participants rated 24 fixed-viewpoint perspectives of virtual rooms with varying window fenestration and roof forms for their feelings of enclosure and exposure. As the stimuli in this study are the varying views from a room, isovist properties were derived from the room geometry

as a measure for the spatio-visual dimension of each space. The survey results were then compared with the actual or metric spatial properties (for example, *the wall-to-window-area ratio*) as well as with commonly used isovist measures (for example, *isovist area*) that have been derived from both plan- and section-based isovists. All isovists were constructed with a uniform view limit of 20 metres from the observation point. Decisions about the view limits used in isovist analysis must balance the fact that longer limits inflate many calculated measures – they increase isovist perimeter, isovist area and occluded radials – without adding any additional benefit to the calculations and complicating comparisons using non-ratio based measures. A practical view limit must also extend beyond the immediate environment being analysed but not so far that it includes distant objects. The chosen 20 metre view limit balances these factors and reinforces the notion that the interior and its general relationship with the exterior are the focus, and not any distant views.

The test environment and stimuli

For this study an interior was modelled which represents a habitable domestic room of contemporary style, including some neutrally-styled and coloured furniture along with some small, personal objects (books, paintings and a floor lamp). These objects are included to give the room scale, and allow the viewer to more intuitively understand its setting. Each virtual room has a 5 x 5 meters wide plan and, for most of the rooms, a standard ceiling height of 2.4 meters. 24 controlled variations of the room were then produced. Each room has one of three opening types: a narrow window band or “slot” (A), a full height opening that is interrupted by columns (B), and a full height opening with no columns (C). These openings were then divided by eight room variations, including two ceiling variations and a graduated mix of opening widths (or an increasing number of openings for type B) from room 1 to 8, of which room 1 and 8 depict variations of the ceiling (a downward or upward sloping low skillion), both symbolising an amplified degree of enclosure or exposure (Table 1). Collectively, these 24 variations result from the use of three window heights or style (A – C) variations, each of which are modified by 6 different widths (2 – 7), and two roof angles (1 and 8). Figure 2 shows examples of three of the

stimuli used: (i) room 1 with window type A, the narrow window band, (ii) room 5 with window type B, the full height window divided by columns, and (iii) room 8 with window type C, the full height opening. All stimuli show the same backdrop image – a view of trees and a stream – which has been reduced to an opacity of 30% so as not to compete for attention with the room itself. The decision about opacity was also taken to reinforce the importance of the interior and its general outlook, but not the exact properties of the distant views. This also effectively replicates the fact that the human eye must focus at a particular distance – generally on either the foreground or the background of a space – and the reduced opacity of the backdrop assists the participants to stay focussed on the varying foregrounds.

Figure 2

The participants

Staff and students from eight universities from across the world were invited to take part in the study. The majority of the participants was from Australia (57%), followed by Europe (20%) and Asia (16%), and with 5% ‘others’ who form the smallest group. 91 of the 159 respondents were male and the age groups ranged from 18 to 70. Not surprisingly, the largest percentage of participants belongs to the youngest age group (44%, age: 18 to 25) followed by the second group (23%, age: 26 to 35) and the third (19%, age: 36 to 45), while participants over the age of 45 form the smallest group (14%). The majority of participants (62%) had some level of training in architectural design. Most participants spent their youth in suburban (43%) or urban (34%) areas, with rural or countryside areas in the minority (23%). These participants lived during the past ten years in suburban (40%) and urban (46%) areas, with only 13% in rural areas. The majority of Asian (84%) and European (60%) participants lived during the past ten years in an urban area, and also 60% of all European participants lived in an urban environment. Most participants lived more recently in suburban areas (Australia: 52%; other: 63%). Participants who had no architectural training are represented most equally across all age groups.

Implementation

Participants took part in an online questionnaire which was accessible for a period of eight weeks. Seven demographic questions followed an initial agreement on reading the information statement, asking for age, gender, experience, current location (country) and local background. Thereafter, a short description of the terminology used and three example images (Figure 2) were shown before the first stimuli. The explanatory text is as follows:

The following images show typical examples of the range of test images you will be asked about. Furniture and fittings in the room are just to give a sense of scale – the focus is on the nature of the relationship between walls, openings, ceiling heights and sill heights. Please examine each of the test images and rate every room on a scale from (1) ‘strongly disagree’ to (7) ‘strongly agree’ for your feelings of enclosure (feeling concealed or hidden) and exposure (feeling exhibited or exposed).

The two questions asked for each image – “Do you feel enclosed in this room? Do you feel exposed in this room?” – aim to uncover the participant’s true feelings or perceptions in response to the varying room dimensions.

The 24 stimuli were then presented in the order shown in Table 1, varying by opening type. While ordered stimuli can influence the assessment, it can also be argued that a fixed structure aids the overall understanding of the rating task. Past research suggests that most viewing conditions (for example, light levels, time of the day and presentation orders), under which the stimuli are viewed, can be disregarded as different respondents or scaling lead to the same results (Stamps 2006). Of greater importance is allowing a reasonable time limit for the assessment process, as a too short presentation time can cause stress and ill-considered decisions, while an increased length of a survey may result in fewer submissions (Dosen and Ostwald 2013).

Room and isovist properties

The stimuli were grouped by opening types (A to C) and increasing opening widths and roof angles (room 1 to 8). The actual degree of enclosure of each variation was measured using the

area and *perimeter* of openings, *the wall-to-window-area ratio* and *opening width*. Six isovist measures were developed for each room, including *isovist area*, *perimeter* and their *ratio A/P*, along with *roundness (R)* (which is isovist area divided by the squared isovist perimeter length) (both an indicator of combined prospect and refuge), *openness (O)* (which is open edges divided by closed edges) (indicator for prospect or refuge) and *isovist-to-room-area ratio* (indicator for openness or enclosure). These measures are grouped in plan view, in section view and by their sum (plan and sectional isovists) as a simple means of approximating a three-dimensional isovist.

Importantly, the purpose of this paper is to examine whether participants' perceptual ratings do relate to the actual properties of quite simple architectural spaces. As such, a very high correlation of the actual room properties and the mean ratings of perceived enclosure and exposure will affirm people's capability to perceive the geometry of a space. The spatio-visual dimensions of the rooms, which influences the lived experience of an environment, is measured with the most relevant isovist properties. A high correlation of mean ratings with these specific isovist measures will confirm a link between lived space and geometric space, while a high correlation of isovist measures with the wall-to-window-area ratio would confirm the isovist's measures usefulness. As enclosure and exposure can be considered reciprocal properties (an increase in one reduces the other), a high negative correlation can be as informative as a high positive one. Indeed, it is anticipated that, for example, increasing isovist area should both increase perceptions of exposure and reduce perceptions of enclosure.

Results for enclosure

Perceptual responses for enclosure

The distribution of averaged responses for perceived enclosure illustrates a general downward trend for all lines in the chart, which represent the three opening types (A, B or C) for all room variations (1 to 8) of each virtual environment (Figure 3). All trend lines indicate a similar fall, which confirms that feelings for enclosure are highest when the windows in a room are smaller (room 1), and lowest when the windows are larger (room 8). The minimum and maximum ratings

for perceived enclosure always range, with one exception, from 1 to 7 (on a 7-point-Likert scale) for each of the 24 room variations. Thus, at least one of the 159 respondents always felt either very enclosed, or not at all enclosed, regardless of the room geometry. The standard deviation is highest for rooms A8 (1.863, mean for A: 1.596) and B8 (1.744, mean for B: 1.540) while the lowest standard deviation occurs for room C8 (1.344, mean for C: 1.485). This suggests that there is most agreement on rating perceived enclosure for room 8 of type C (the widest and largest opening) and least agreement on assessing room 8 of type A (the largest opening width of the narrow height window band).

Figure 3

Perceptual responses for enclosure divided by demographic factors

An independent-sample, two-tailed t-test has been used to compare the results of perceptions sorted by demographic data. Overall, the data confirms that, as expected, there are no significant differences in the ratings for perceived enclosure in terms of either gender (correlation coefficient $r_A=0.984$, $r_B=0.970$, $r_C=0.993$ and $p=0.000$ for all three types) or educational background ($r_A=0.978$; $r_B=0.955$; $r_C=0.991$ and $p=0.000$ for all three types). Females rated the window band type higher for enclosure, and those who lived during past ten years in rural areas rated it significantly higher than men from the same, rural background. Architecturally trained participants felt, in 19 out of 24 non-significant cases, less enclosed than those from other backgrounds.

There are only a few differences in relation to the participant's background with only one significant result out of 24. In both cases, where participants grew up and where they lived during past ten years, only room 2 of type A, the smallest window of the narrow opening type was rated significantly higher for perceived enclosure by people from rural areas (mean difference 'where participants grew up': 0.56818; mean difference 'where they lived during past ten years': 0.83438).

There is a significant difference between groups who have a separate bedroom and those who live in a one-room apartment with ratings of the latter group being unexpectedly much higher for perceived enclosure when judging the largest openings. However, the sample size of this division only includes 15 participants in the group who live in a studio or one-room apartment, and therefore this result may not allow for a representative conclusion.

There are also some differences between results by age groups, which indicate that the youngest (and largest) group (age of 18 – 25 years) seem to feel more enclosed than older participants. A comparison of the ratings divided by continent shows no significant difference between the ratings of the three large groups. The European participants (30%) rated opening types B and C the most consistently in terms of enclosure whereas Australians (59%) judged the first stimuli slightly higher for feelings of enclosure in comparison to the Asians (26%), who judged the larger openings of all types on average higher for feelings of enclosure than all other participants.

Perceptual responses for enclosure compared with room properties

For the statistical comparison of perceptual responses and measured properties of the virtual rooms a Pearson's Product Moment Correlation was used to quantitatively describe their relationship. The correlation coefficient r was determined by averaging rating results of each room ($N=8$) for perceived enclosure by opening type (three variables). Overall, the results show an extremely high and positive correlation between the perceptual responses for enclosure and the wall-to-window-area ratio – the most precise room property for the actual enclosure for each individual room variation – with values close to 1 ($r_A=0.8396$, $r_B=0.8785$ and $r_C=0.9321$) (Table 2). A significance test determines a probability of less than one percent that this is a chance finding ($p_A=0.0091$, $p_B=0.0041$ and $p_C=0.0007$). The values for the opening area show, as expected, a high, negative correlation with the mean ratings for perceived enclosure with a significant correlation at the 0.05 level for opening type B and 0.01 level for opening types A and C ($r_A=-0.969$, $r_B=-0.807$ and $r_C=-0.860$; $p_A=0.000$, $p_B=0.015$ and $p_C=0.006$). The results for both perimeter and opening width show and even higher, negative correlation.

Figure 4

Overall, the room measurements – except for the wall-to-window-area ratio, a measure for enclosure – indicate a very high, negative correlation with the average ratings for enclosure, meaning that the larger the actual opening, the less the feeling of enclosure (Figure 4). This confirms that the mean ratings (perceived, lived space) match the room dimensions (actual, geometric space), a fact which verifies the general reliability of the averaged survey responses.

Perceptual responses for enclosure compared with isovist properties

The plan isovist properties, along with the sum of sectional and plan isovist properties show, as expected, a relatively high, mostly negative correlation with the mean ratings for enclosure (Table 3). However, for opening type B (the one divided by columns) the plan isovist area-to-perimeter ratio and roundness measures, which can be indicators of both prospect and refuge conditions, show a positive correlation (moderate high and very high) with the mean ratings for enclosure. This may indicate an opposite trend for opening type B as there exists more opportunity to hide than in the other room types. To confirm this hypothesis (or explanation of the opposite trend) also the plan isovist perimeter would be expected to vary for type B as the perimeter length is much higher due to its division by columns, but the results do not identify such a difference. Another explanation might be that measure of ratios result in much larger values and therefore show some differences while a single measure does not. In contrast, the sectional isovist properties display no significant relationship with the mean ratings for perceived enclosure and are therefore less useful than might be expected. Admittedly, sectional isovists are only rarely used in computational analysis and, unlike plan isovists, have never been specifically tested for correlation with actual perceptions. The sum of plan and section isovist measures indicates a negative correlation with the results for perceived enclosure. Most of these summarised measures show a similar opposite trend for opening type B as in the plan isovist results. However, the sum of the isovist-area-to-perimeter ratio does not show a correlation at all for opening type B. The

isovist-area-to-perimeter ratio is, in general, a plan-related ratio and does not change in value in the same way as the sum of plan and sectional isovists and therefore it is not a suitable measure for the third group of isovists.

A correlation test of the isovist-to-room-area ratio (incorporating both a geometric measure and isovist measure) with perceived enclosure indicates the highest, negative correlation across all three opening types ($r_A=-0.946$, $r_B=-0.966$ and $r_C=-0.962$). This is the expected result as a simple, convex layout of an interior with an increasing number of openings will produce a larger value for the degree of openness than a room would do that has less openings or none.

Overall, these results confirm the usefulness of plan isovist measures though there are limitations in capturing differences of all room variations. This is because opening types A and C have the same plan isovist properties (it is the sectional properties that differentiate them). Although the sum of sectional and plan isovists also indicates a relatively high, negative correlation for most isovist properties with perceived enclosure, this category may require more attention in future studies to better develop a scheme for using this isovist group more effectively as an approximation for three-dimensional isovist properties.

Results for exposure

Perceptual responses for exposure

The distribution of averaged responses for perceived exposure illustrates a general upward trend for all lines in the chart, which represent the three opening types (A, B or C) for all room variations (1 to 8) of each virtual environment (Figure 5). The trend lines indicate a similar rise, which confirms that feelings for exposure are highest when the windows in a room are larger (room 8), and lowest when the window openings are smaller (room 1). Furthermore, the mean values of perceived exposure in respect of opening type A remain one rated value higher than those of opening type B, and those of type B have a similar difference to the ratings of type C. Thus, the full height opening without columns was rated as the most exposing, the full height window with

columns as intermediate and the narrow window band was judged as the least exposing. Overall, there is a clear, if irregular rise across the trend lines from room variation 1 to room variation 8.

Figure 5

The minimum and maximum ratings for perceived exposure in these results always range from 1 to 7 (on a 7-point-Likert scale) for each of the 24 room variations. The standard deviation increases with increased opening size, meaning there is less agreement on feelings of exposure the larger the opening is. In particular, the larger openings of type B (the full height opening divided by columns) and C (the full height openings without columns) indicate a level of disagreement with the highest standard deviation for room C7 (the widest and largest opening with a flat ceiling; 1.879), followed by C8 (with the rising ceiling; 1.847, mean for C: 1.637). Also, room 8 of type B shows less agreement with a standard deviation of 1.881 (mean for B: 1.483), while the ratings for the smaller openings of type A (the narrow window band) indicate more agreement (highest value for standard deviation: A8: 1.658, mean for A: 1.407).

Perceptual responses for exposure divided by demographic factors

A division by demographic factors confirms that there are no significant differences in the ratings for perceived exposure when comparing by gender (correlation coefficient $r_A=0.935$, $r_B=0.949$, $r_C=0.982$; $p_A=0.001$, $p_B=0.000$, $p_C=0.000$) or educational background ($r_A=0.970$, $r_B=0.980$, $r_C=0.987$ and $p=0.000$ for all three types). However, females rated the larger openings slightly higher for exposure. Men who lived during past ten years in suburban areas and females from rural areas both felt less exposed than others. Architecturally trained participants rated the stimuli throughout slightly higher for perceived exposure, but only three of the 24 cases produced greater differences in perceptions at a 5% probability level. These differences are all for type A, the narrow window band, which suggests that a background in architectural design does not strongly influence feelings for exposure as the larger openings (which are more likely to evoke feelings of exposure) were rated very similarly by both groups.

Participants who grew up in an urban area felt, on average, slightly more exposed, which might be regarded as an expected result for people living in close proximity to others. People who lived during past ten years in suburban areas felt least exposed, though the mean difference is always less than half a rating point (on a 7-point scale). Those who live in a one-room apartment feel, not surprisingly, more exposed than others. The largest differences occur for room 2 and 7 of opening type A with a mean difference of 0.866 (A2: $p=0.009$) and 1.115 (A7: $p=0.009$).

Interestingly, younger participants felt on average more exposed than older ones, with the largest difference of mean ratings between the youngest (age 18 to 25) and oldest age group (46 or above). Altogether in 14 of 24 cases the mean difference was significant at a 5% probability level with the highest being 1.725 for room 7 of type C ($p=0.001$). Also, it appears that younger participants tend to provide higher scores than older ones.

A comparison by the participants' geographic background (by continent) indicates that Asian participants (26%) rated their feelings for exposure on average higher than other groups. The lowest ratings were provided by the 'other' group (including North-America and Africa) which are, in comparison to the results from Asia, up to two scores lower (on a 7-point-Likert scale) while the perceptions for exposure of the three larger groups vary around one value on the rating score. The difference between the groups increases slightly with increasing opening size in a room. The smallest difference occurs between the ratings of participants from Asia and Europe, of which in both cases the majority of participants lived during past ten years in urban environments.

Perceptual responses for exposure compared with room properties

A comparison of mean ratings for perceived exposure with the wall-to-window-area ratio (a measure for enclosure) indicates a very similar, but opposing trend (means rise not fall) and, as expected, a very high, negative correlation between the two (Figure 6). The correlation coefficient for type A is $r_A=-0.908$ ($p_A=0.002$), for B: $r_B=-0.912$ ($p_B=0.002$) and C: $r_C=-0.917$ ($p_C=0.001$), meaning perceptual responses match the actual geometric dimensions of the space (Table 2). In more detail, the ratings for the window band show a similar peak when the wall-to-window-area

ratio has a low point and vice versa. These similarities occur for rooms 3, 4, 7 and 8 while the first two openings have been rated slightly too high for a true inverse trend. The other metrics, including the area and perimeter of openings and the opening width show also a very high, but positive correlation with perceived exposure of which opening area has, on average, the lowest correlation results with A: $r_A=0.922$ ($p_A=0.001$), B: $r_B=0.874$ ($p_B=0.005$) and C: $r_C=0.770$ ($p_C=0.025$).

Figure 6

Perceptual responses for exposure compared with isovist properties

The majority of the plan isovist properties display a relatively high, positive correlation with perceptions of exposure (Table 4). A correlation test of the isovist-to-room-area ratio (incorporating both a geometric measure and isovist measure) with perceived enclosure indicates the highest, positive correlation across all three opening types ($r_A=-0.897$, $r_B=-0.962$ and $r_C=-0.943$). That is, the larger the spatio-visual geometry of a room, the greater the feeling of exposure. Also, isovist area and perimeter correlate very highly with perceptions for all opening types. The three exceptions to this occur for the isovist measures isovist-area-to-perimeter ratio, roundness and openness, and all for room type B which, as a result of the addition of columns, has a much larger isovist perimeter length; a factor which leads to several marginal to high negative correlations. Overall, this implies that, within the limits of the present study, perimeter length is not a strong determinant of feelings of exposure. The sectional isovist properties, once again, show no significant relationship with perceptual responses. While there may be multiple reasons for this result, which are beyond the scope of the present research, a complicating factor is that the larger opening types B and C have identical sectional isovists. Thus, there may be insufficient variation in the sectional isovists tested for examining the variations between these.

The sum of sectional and plan isovists shows a similar but less emphatic, positive correlation with the data for perceived exposure for opening types A and C. The data also reveals

the same exceptions for opening type B in the form of a negative correlation with perceptions of exposure for isovist roundness and openness while there is no correlation at all for isovist-area-to-perimeter ratio: a result which may have been skewed by the low value of the sectional isovist. In the other cases the larger type B opening influences the formula and creates a low or negative value.

Conclusions

In total, for 24 different spaces, the paper compares four measured room properties (the actual geometry of each room) and five isovist properties in three variations, with ratings for perceived enclosure and perceived exposure, providing a rich, detailed and methodical analysis of a basic assumption in design psychology and architectural science.

The first question asked in this paper is, what is the relationship between human perceptions of enclosure and exposure, and the geometrical attributes of environments? Past research suggests that spatial and spatio-visual geometry influences environmental preference (Scott 1993a; b; Carter 2002; Lidwell, Holden, and Butler 2003; Dalton et al. 2010). For example, Joedicke (1985) describes spaciousness as a major component of the emotional experience of architecture while other researchers confirm a strong correlation between spaciousness and perceptions of beauty (Franz et al. 2004; Wiener et al. 2007; Dzebic 2013). Stamps (2006) highlights width as an important spatial factor shaping perceptions of comfort in an interior. However, very few studies test, in a controlled way, the relationship between actual spatial properties and how they are perceived. One rare exception (Wiener et al. 2007) confirms the ability of participants to identify the most hidden or exposed place in an interior by comparing survey results with an analysis of isovist areas.

The results presented in this paper indicate a very high, positive correlation of the mean results for perceived enclosure (lived space) with the room properties (geometric space) of the virtual interiors (for example, wall-to-window-area ratio: $r = 0.842$) and a very high negative correlation with the mean results of perceived exposure ($r = -0.909$). Overall, this confirms that human perceptions of relative environmental conditions, like enclosure and exposure, are

generally accurate. The study also shows that many demographic variables including gender and educational background reveal no significant differences in this capacity. However, the local background of participants (where they grew up or lived), does account for some differences in spatial perception. For example, participants who grew up in a suburban environment rated all rooms lower for their feelings of enclosure and exposure than those who grew up in rural or urban areas (highest ratings). This result broadly supports the idea that it is not only the physical space itself that is being perceived and assessed, but that past experience also shapes perceptions and preferences (Ellard 2009, Tuan 2013). Such findings can inform future research which examines lived experiences in a larger, environmental context and how these shape feelings and impressions.

The second question asked in this paper is, which computational measures correlate most closely with human perceptions? Past research has generally noted the usefulness of isovist analysis for predicting experiential qualities of space (Wiener et al. 2007; Meilinger et al. 2012) but only isovist area has previously been identified as a dominant factor (Franz et al. 2004). The comparison of isovist data indicates that only certain measures are suitable for representing the geometric properties of a virtual interior with a simple, rectilinear plan. In particular, the isovist measures that have been derived from the sectional isovists do not show a significant relationship with the perceptual responses (the one exception being openness), whereas all plan isovists but occlusivity, a measure for mystery, for opening types A and C present a very high correlation. More specifically, isovist area, isovist perimeter and isovist-to-room-area ratio indicate a high, negative correlations with perceptions of enclosure for all opening types (and vice versa for perceptions of exposure), while for other isovist measures, opening type B always shows the opposite trend. Furthermore, a comparison of plan isovist measures with the geometric property wall-to-window-area ratio confirms a high to very high correlation. However, several secondary measures appear to be less effective or useful including isovist area-to-perimeter ratio and roundness (both an indicator for combined prospect and refuge).

Overall, the combined method used in the present paper – surveying participants and testing their responses for a relationship with room measures and isovist properties – proves to be

a valuable approach to learn more about the relationship between lived and geometric space. However, there are limits to the present research that must also be taken into account when interpreting the results. In particular, internal prospect was not considered in the present study and it has rarely been examined in past research. For examining internal prospect, three-dimensional isovist or spatial salience measures (Fisher-Gewirtzman et al. 2003; Bhatia et al, 2013) may be more useful. Additionally secondary elements of a test environment could also be varied to determine if they influence perceptions. These elements include colour, style, texture and exposed structure. A further limitation of the present study is its use of a fixed observation point for each stimuli. Finally, the present research demonstrates that information about participants' backgrounds (where they grew up or lived for a long time) is seriously lacking in past research and may have a larger impact on spatial preference than architectural studies in this field anticipate. In many countries, the majority of people live in dense, urban environments, and this potentially shapes their experience of space (Cheng 2010; Fisher-Gewirtzman 2016).

The philosophical notions of lived and geometric space have often been used by architectural theorists and historians as a means of juxtaposing different attitudes. For example, the former has been linked to phenomenological reasoning and the latter to scientific or positivist thinking. However, in contemporary design theory, the results of environmental preference research have been uncritically extrapolated in such a way as to ignore the potential difference between the two, and just assume that spatial perceptions are always accurate. The present research confirms that, for a simple room and a graduated series of variations, basic human spatial perceptions do correlate to the metric properties of a space. This finding certainly doesn't support the assumption that, for practical purposes, lived and geometric spaces are the same. However, it does suggest that some human spatial perceptions reflect the properties of a room's actual geometry, and some metric and isovist measures can legitimately be used to model or predict relative spatial perceptions.

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Table 1. Stimuli by opening type (A – Window band, C – Full height opening divided by columns, and C – Full height opening) and room variations (1 – 8).

	A	B	C
1
2

3

4

5

6

7

8

Table 2. Pearson's correlation coefficient r and probability p for mean ratings of perceived enclosure and exposure with room measures. ** significant at 1% level * significant at 5% level

Measures of opening(s)	Results for enclosure	Results for exposure
Area	$r_A = -0.969^{**}$ $p_A = 0.000$ $r_B = -0.866^{**}$ $p_B = 0.005$ $r_C = -0.811^*$ $p_C = 0.015$	$r_A = 0.922^{**}$ $p_A = 0.001$ $r_B = 0.874^{**}$ $p_B = 0.005$ $r_C = 0.770^*$ $p_C = 0.025$
Perimeter	$r_A = -0.969^{**}$ $p_A = 0.000$ $r_B = -0.902^{**}$ $p_B = 0.002$ $r_C = -0.934^{**}$ $p_C = 0.001$	$r_A = 0.922^{**}$ $p_A = 0.001$ $r_B = 0.908^{**}$ $p_B = 0.002$ $r_C = 0.888^{**}$ $p_C = 0.003$
Wall-to-window ratio	$r_A = 0.842^{**}$ $p_A = 0.009$ $r_B = 0.872^{**}$ $p_B = 0.005$ $r_C = 0.931^{**}$ $p_C = 0.001$	$r_A = -0.909^{**}$ $p_A = 0.002$ $r_B = -0.903^{**}$ $p_B = 0.002$ $r_C = -0.917^{**}$ $p_C = 0.001$
Opening width	$r_A = -0.969^{**}$ $p_A = 0.000$ $r_B = -0.977^{**}$ $p_B = 0.000$ $r_C = -0.984^{**}$ $p_C = 0.000$	$r_A = 0.922^{**}$ $p_A = 0.001$ $r_B = 0.961^{**}$ $p_B = 0.000$ $r_C = 0.936^{**}$ $p_C = 0.001$

Table 3. Pearson's correlation coefficient r and probability p for mean ratings of perceived enclosure with isovist measures. Note that the isovist-to-room-area ratio is only useful in plan isovists. ** significant at 1% level * significant at 5% level

Isovist measures	Plan isovist	Sectional isovist	Σ plan + sectional isovist
Area	$r_A = -0.946^{**}$ $p_A = 0.000$ $r_B = -0.966^{**}$ $p_B = 0.000$ $r_C = -0.958^{**}$ $p_C = 0.000$	$r_A = -0.054$ $p_A = 0.899$ $r_B = -0.560$ $p_B = 0.149$ $r_C = -0.487$ $p_C = 0.220$	$r_A = -0.928^{**}$ $p_A = 0.001$ $r_B = -0.898^{**}$ $p_B = 0.002$ $r_C = -0.899^{**}$ $p_C = 0.002$
Perimeter	$r_A = -0.926^{**}$ $p_A = 0.001$ $r_B = -0.983^{**}$ $p_B = 0.000$ $r_C = -0.944^{**}$ $p_C = 0.000$	$r_A = 0.170$ $p_A = 0.688$ $r_B = -0.344$ $p_B = 0.404$ $r_C = -0.227$ $p_C = 0.588$	$r_A = -0.798^*$ $p_A = 0.018$ $r_B = -0.984^{**}$ $p_B = 0.000$ $r_C = -0.788^{**}$ $p_C = 0.020$
Area-to-perimeter ratio	$r_A = -0.958^{**}$ $p_A = 0.000$ $r_B = 0.701$ $p_B = 0.053$ $r_C = -0.972^{**}$ $p_C = 0.000$	$r_A = -0.160$ $p_A = 0.706$ $r_B = -0.589$ $p_B = 0.124$ $r_C = -0.526$ $p_C = 0.181$	$r_A = -0.945^{**}$ $p_A = 0.000$ $r_B = 0.013$ $p_B = 0.976$ $r_C = -0.929^{**}$ $p_C = 0.001$
Roundness	$r_A = -0.969^{**}$ $p_A = 0.000$ $r_B = 0.968^{**}$ $p_B = 0.000$ $r_C = -0.977^{**}$ $p_C = 0.000$	$r_A = -0.346$ $p_A = 0.402$ $r_B = -0.638$ $p_B = 0.089$ $r_C = -0.595$ $p_C = 0.120$	$r_A = -0.959^{**}$ $p_A = 0.000$ $r_B = 0.903^{**}$ $p_B = 0.002$ $r_C = -0.950^{**}$ $p_C = 0.000$
Openness	$r_A = -0.913^{**}$ $p_A = 0.002$ $r_B = 0.965^{**}$ $p_B = 0.000$ $r_C = -0.925^{**}$ $p_C = 0.001$	$r_A = 0.491$ $p_A = 0.217$ $r_B = -0.383$ $p_B = 0.349$ $r_C = -0.272$ $p_C = 0.514$	$r_A = -0.082$ $p_A = 0.847$ $r_B = 0.921^{**}$ $p_B = 0.001$ $r_C = -0.751^*$ $p_C = 0.032$
Isovist-to-room-area ratio	$r_A = -0.946^{**}$ $p_A = 0.000$ $r_B = -0.966^{**}$ $p_B = 0.000$ $r_C = -0.962^{**}$ $p_C = 0.000$	N/A	N/A

Table 4. Pearson's correlation coefficient r and probability p for mean ratings of perceived exposure with isovist measures. Note that the isovist-to-room-area ratio is only useful in plan isovists. ** significant at 1% level * significant at 5% level

Isovist measures	Plan isovist	Sectional isovist	Σ plan + section isovist
Area	$r_A = 0.897^{**}$ $p_A = 0.003$ $r_B = 0.962^{**}$ $p_B = 0.000$ $r_C = 0.949^{**}$ $p_C = 0.000$	$r_A = -0.140$ $p_A = 0.740$ $r_B = 0.588$ $p_B = 0.125$ $r_C = 0.461$ $p_C = 0.250$	$r_A = 0.863^{**}$ $p_A = 0.006$ $r_B = 0.909^{**}$ $p_B = 0.002$ $r_C = 0.874^{**}$ $p_C = 0.004$
Perimeter	$r_A = 0.867^{**}$ $p_A = 0.005$ $r_B = 0.973^{**}$ $p_B = 0.000$ $r_C = 0.912^{**}$ $p_C = 0.002$	$r_A = -0.373$ $p_A = 0.363$ $r_B = 0.337$ $p_B = 0.414$ $r_C = 0.183$ $p_C = 0.665$	$r_A = 0.671$ $p_A = 0.069$ $r_B = 0.974^{**}$ $p_B = 0.000$ $r_C = 0.744^*$ $p_C = 0.034$
Area-to-perimeter ratio	$r_A = 0.914^{**}$ $p_A = 0.002$ $r_B = -0.671$ $p_B = 0.068$ $r_C = 0.955^{**}$ $p_C = 0.000$	$r_A = -0.019$ $p_A = 0.964$ $r_B = 0.623$ $p_B = 0.099$ $r_C = 0.504$ $p_C = 0.203$	$r_A = 0.894^{**}$ $p_A = 0.003$ $r_B = 0.042$ $p_B = 0.921$ $r_C = 0.909^{**}$ $p_C = 0.002$
Roundness	$r_A = 0.932^{**}$ $p_A = 0.001$ $r_B = -0.945^{**}$ $p_B = 0.000$ $r_C = 0.967^{**}$ $p_C = 0.000$	$r_A = 0.215$ $p_A = 0.610$ $r_B = 0.683$ $p_B = 0.062$ $r_C = 0.581$ $p_C = 0.131$	$r_A = 0.938^{**}$ $p_A = 0.001$ $r_B = -0.856^{**}$ $p_B = 0.007$ $r_C = 0.941^{**}$ $p_C = 0.000$
Openness	$r_A = 0.889^{**}$ $p_A = 0.003$ $r_B = -0.947^{**}$ $p_B = 0.000$ $r_C = 0.958^{**}$ $p_C = 0.000$	$r_A = -0.626$ $p_A = 0.097$ $r_B = 0.382$ $p_B = 0.350$ $r_C = 0.230$ $p_C = 0.583$	$r_A = 0.112$ $p_A = 0.792$ $r_B = -0.909^{**}$ $p_B = 0.002$ $r_C = 0.765^*$ $p_C = 0.027$
Isovist-to-room-area ratio	$r_A = 0.897^{**}$ $p_A = 0.003$ $r_B = 0.962^{**}$ $p_B = 0.000$ $r_C = 0.943^{**}$ $p_C = 0.000$	N/A	N/A

Figure 1. Isovist viewshed polygon of the basic room shape tested with four window openings.

Figure 2. Example of three stimuli varying in ceiling and opening types.

Figure 3. Mean of ratings for perceived feelings of enclosure by opening type (A – C) and increasing opening width (room 1 to 8).

Figure 4. Correlation coefficient r for mean ratings of perceived enclosure with actual, geometric room properties.

Figure 5. Mean of ratings for perceived feelings of exposure by opening type (A – C) and increasing opening width (room 1 to 8).

Figure 6. Correlation coefficient r for mean ratings of perceived exposure with actual, geometric room properties.

Figures attached as separate files / overview only.

Chart fonts can be modified here (not in attached eps file format).

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6