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Embodied 3D isovists: A method to model the visual perception of space

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Abstract

Isovist analysis has been typically applied for the study of human perception in indoor built-up spaces. Albeit predominantly in 2D, recent works have explored isovist techniques in 3D. However, 3D applications of isovist analysis simply extrapolate the assumptions of its 2D counterpart, without questioning whether these assumptions remain valid in 3D. They do not: because human perception is embodied, the perception of vertical space differs from the perception of horizontal space. We present a user study demonstrating that an *embodied 3D isovist* that accounts for this phenomenon (formalised based on the notion of *spatial artefacts*) predicts human perception of space more accurately than the generic *volumetric 3D isovist*, specifically with respect to *spaciousness* and *complexity*. We suggest that the *embodied 3D isovist* should be used for 3D analyses in which human perception is of key interest.

Keywords

Isovist, 3D isovist, architectural analysis, spatial artefacts, visuo-locomotive experience, perception

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Introduction

An isovist is defined as the set of all points visible from the given vantage point in space. Despite being originally considered as a three-dimensional concept (Benedikt, 1979), isovists have typically been implemented as 2D or 2.5D computational models of visibility. Recently, however, it has become more viable to compute isovists in 3D. It is therefore timely to consider how the traditional 2D implementation is extended to 3D and what this means to the original meaning of isovists.

A direct extrapolation of the classic 2D method to the third dimension yields an isovist equivalent to the unweighted volume of geometrical space visually accessible from its vantage point (from now on referred to as the *volumetric 3D isovist*). It is the position of this paper that such computation is an oversimplification of what isovists were originally intended to represent. The shape and size of isovists are meaningful strictly because they are assumed to carry information accessible and relevant to a hypothetical human explorer of that space, such as information about the potential attractiveness of the view (Shach-Pinsly et al., 2011); co-visibility of settlements (Brughmans et al., 2015); navigational choice available at a junction (Meilinger et al., 2012); emotional associations with the geometric shape of space (Wiener et al., 2007); visibility of art exhibits (Krukar and Conroy Dalton, 2013; Krukar and Dalton, 2020); orienting information during rotational locomotion (Kondyli and Bhatt, 2018) and wayfinding (Kondyli et al., 2018). Consequently, the vantage point of the isovist represents a possible location of the *human* eye, or a location potentially visible by the *human* eye. Thus, the properties of the human body and of the human visual system are central to isovist analysis (Bhatt and Schultz, 2014; Conroy Dalton, 2005; Kondyli et al., 2017; Montello, 2007).

These properties are not identical in the vertical compared to the horizontal plane: our field of view is wider than higher, most of our locomotion happens along the horizontal plane, and we typically care more about the information distributed along the horizontal plane. We perceive space that is *above* us differently than the same volume of space *below*. Affordances of space *to the left* and *to the right* are similar or identical, while affordances of space *above* and *below* are not. Directly extrapolating the traditional 2D analysis into the third dimension ignores these characteristics of the human body, our visual system and our practical relation to space. In consequence, the generic volumetric 3D isovist computation does not fulfil the same function as its 2D predecessor was envisioned to.

To address this, we investigate the concept of the *embodied 3D isovist*, a type of *spatial artefact* (Bhatt et al., 2012) that adopts richer notions of 3D visibility by distinguishing semantic perceptual-locomotive sub-regions of the generic volumetric 3D isovist (Bhatt et al., 2012, 2014; Bhatt and Freksa, 2015; Krukar et al., 2017). The embodied 3D isovist is derived by explicitly incorporating salient properties of *space* from the standpoint of embodiment and cognitive psychology, as well as the semantics of the environment itself with respect to the affordances of human visuo-locomotion. In this study, we distinguish between *horizontal* and *vertical* space, as well as between the space *above* and the space *below* a vantage point. We formalise these sub-regions as classes by extending the '*range space*' spatial artefact (Bhatt et al., 2012) class within the *InSpace3D* framework (Bhatt et al., 2012, 2014; Bhatt and Freksa, 2015; Schultz and Bhatt, 2013).

A central contribution of this paper is a user study that empirically demonstrates how metrics that quantify the changing relationships between these sub-regions of an embodied 3D isovist capture key distinctions in the subjective visual impression of spaciousness and complexity in various environments. In the user study, the metrics of 3D isovists were systematically varied in prototypical building models, implemented in a Virtual Reality setting. Participants were asked to rate their impressions of those spaces. We hypothesised that the *embodied 3D isovist* will be a more accurate predictor of human perception, i.e. that the statistical model that considers *embodied 3D isovist* metrics as predictors will result in a better fit to the experimental data than the otherwise identical model limited to the generic *volumetric 3D isovist* metrics.

Background

The concept of the *isovist* was introduced by Hardy (1967) and Tandy (1967) and popularised by Benedikt (1979). Isovists were intended to help predict spatial behaviour and the perception of building visitors by quantifying the geometry of space visible from the specified vantage point (Benedikt, 1979). Benedikt operationalised the isovist as a polygon covering the portion of the environment visible from its single vantage point in a top-down view. He derived a number of metrics that can be used to describe the isovist's geometry, suggesting their relevance to the spatial experience of a building user. Two lines of research developed from this hypothesis, investigating the influence of isovist measurands on: (a) human subjective judgement of space and (b) human performance and decision making in spatial tasks. Our research aims to extrapolate this analysis into three-dimensional spaces, particularly building interiors where vertical space plays a prominent role in perceiving, understanding and navigating through the environment. Specifically, buildings in which the amount of open space above the visitor changes as one moves through it might benefit from three-dimensional visibility analysis, compared to its two-dimensional counterpart. This is because the vertical component of visibility is not uniform throughout the interior and therefore the building users' perception is likely to change, depending on the vertical characteristic of the surrounding space.

Embodied perception and related limitations of the generic volumetric 3D isovist

Human perception is *embodied*, meaning that human capacities and strategies of perceiving the world depend on the organisation of the body (Clark, 1999). The organisation of the body affords and limits certain actions and behaviours (Robbins and Aydede, 2009). For example, the body is symmetric horizontally; we can therefore do similar things, in similar ways with the left side of our bodies, and towards the left of our bodies, as we can with, and towards, the right. The body is also vertically asymmetric. We therefore do different things with the bottom part, than we do with the upper part (Tversky, 2009). Additionally, the body has to counter the force of gravity. Doing the same things downwards therefore feels different than doing them upwards. For instance, walking is more strenuous uphill compared to downhill but walking to the left feels similar as walking to the right. This affects how we perceive space, with features that require more effort appearing disproportionally more strenuous (Proffitt, 2006).

The organisation of the visual system is also asymmetric: our visual field is wider than higher (Strasburger and Pöppel, 2002). People do not visually scan the entire environment in equal proportions since the majority of relevant information during locomotion (e.g. identifying available navigational alternatives) appears along the horizontal axis, and not the vertical axis (Emo, 2018; Tatler and Land, 2011; Wiener et al., 2012). This is the reason why a 2D isovist analysis performed on the horizontal plane can explain so much of human perception and behaviour. However, when there arises the need to consider the visibility of space on the vertical plane, a direct extrapolation of the logic behind the 2D isovist in the form of the generic *volumetric 3D isovist* carries two major limitations:

1. It treats 1 unit of vertical space as equal to 1 unit of horizontal space.

2. It treats 1 unit of space above the vantage point as equal to 1 unit of space below it.

In consequence, the generic volumetric 3D isovist computation does not fulfil the same function as its 2D predecessor was envisioned to: it does not represent the amount of information relevant to a human visitor standing at its vantage point. It therefore cannot accurately model human perception of space. Thus, a 3D isovist derived by (naively) extrapolating from its 2D counterpart may limit the accuracy of isovist analysis in the studies of human perception inside 3D environments. We investigate a cognitively motivated extension of the 3D isovist that accounts for these phenomena.

Although locomotion is a core component of the human visual system, in the present study we focus on visibility from a *stationary* location as a more direct analogue to the original isovist concept. Our measures are therefore grounded in the fact that human perception is embodied and that embodiment entails the asymmetry of vertical relationships; however, we do not aspire to modelling or predicting the embodied experience in its entirety.

New model: Embodied 3D isovist

Definition

We define the embodied 3D isovist that enables the analysis of three-dimensional space grounded in the way humans perceive and explore information present in the visible shape of that space (Bhatt et al., 2012; Bhatt and Schultz, 2017; Kondyli and Bhatt, 2018; Krukar et al., 2017). In this section, we present an operationalisation of the concept. We then demonstrate how the embodied 3D isovist differentiates between features of architectural space unaccounted for within the classic 2D and the generic volumetric 3D isovist approaches. We present a summarised definition below and in Figure 1. Please refer to supplemental material 1 for details. Our operationalised definition is based on the following steps:

Step (1): Partition all opaque surfaces in the environment into triangles.

Step (2): For each triangle t, compute the visible region t' of the triangle from the given eye position p by clipping regions of t that are occluded by the other triangles.

Step (3): Triangulate each visible region t' to simplify the following step.

Step (4): Each triangle in each t' now forms the base of a visible 'pyramid', with the eye at the apex of the pyramid. The concept of embodiment is now incorporated by considering the absolute orientation of the visible surface with respect to the eye (top, down, left, right, front, back).

Step (5): Calculate the volumes of three-dimensional figures defined by the isovists' vantage point and the three types of surfaces (all walls, all floors and all ceilings).

Measures

In the previous section, we divided the isovist volume into semantically distinct regions based on the orientation of visible surfaces. We will now define relations *between* those regions.

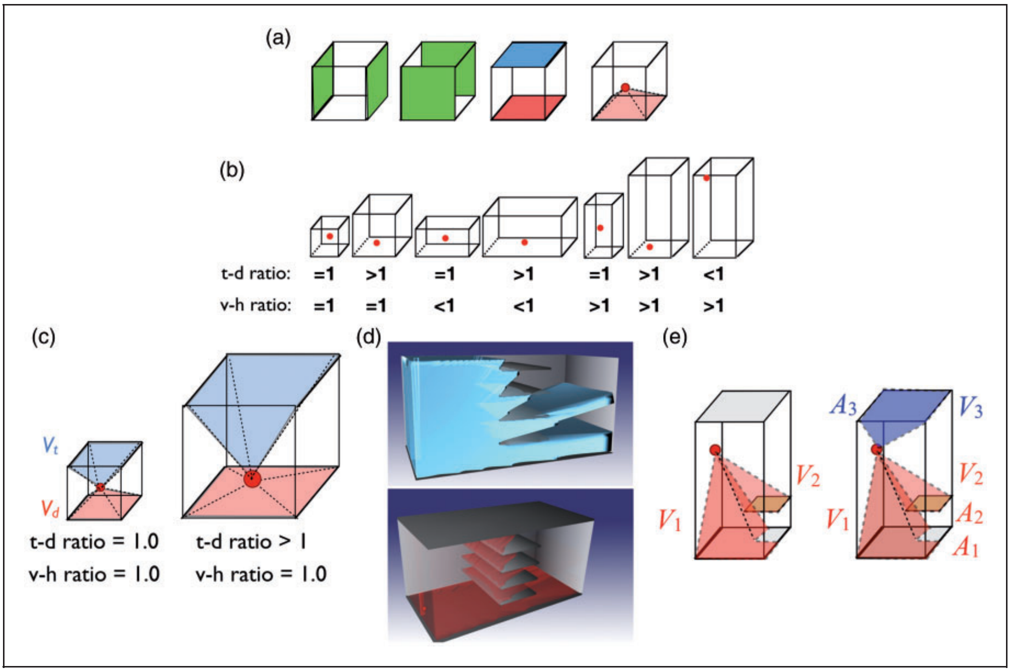

Figure 1. The construction of the embodied 3D isovist: (a) Wall surfaces (green) are considered as equivalent, floors and ceilings (blue and red) are considered to be distinct surfaces. Together with the vantage point, oriented surfaces are used to define the volume of a figure constituting each directional part of the 3D isovist; (b) A schematic (not to scale) representation of the relation between the *v–h ratio* and the *t–d ratio* in convex environments; (c) Two cubes of different dimensions with a vantage point located either in the centre (left) or close to the floor (right). The horizontal pyramids extending to wall surfaces are not visualised, but in both cases the average height of the two vertical pyramids divided by the average height of the horizontal pyramids yields the *v–h ratio* of 1.0; (d) A screenshot of the generic volumetric 3D isovist on a simplified environment of dimensions $40 \times 20 \times 20$, with 'balconies'. The vantage point is located 1.6 units above the floor, near the left-hand-side wall. Note how the balconies occlude the visibility of the opposite wall. This results in decreased volumes of 'horizontal pyramids' (i.e. the portion of the 3D isovist that hits wall surfaces); (e) Left: The total 'downwards volume' is the sum of V_1 and V_2. Right: *Vertical jaggedness* jointly considers downwards and upwards volumes ($V_1+V_2+V_3$), together with all upwards facing and downwards facing visible surface areas ($A_1+A_2+A_3$).

Consider a cube with an isovist vantage point located in its centre. This defines six identical pyramids which share one apex. Each wall, floor, and ceiling surface defines the base of a single pyramid. The *height* of each pyramid is the distance from the base to the apex, in the direction of the normal of the base. The volume of a pyramid with *base* area and *height* is

$$volume = \frac{1}{3} \cdot base \cdot height$$

We refer to pyramids with a floor or ceiling base as *vertical pyramids*, and we refer to pyramids with a wall base as *horizontal pyramids*. The relation of the average height of two vertical pyramids to the average height of all four horizontal pyramids equals $0.5/0.5 = 1$. We refer to this as the *vertical-to-horizontal ratio*, or *v–h ratio*. The relation of the top-surface pyramid volume to the bottom-surface pyramid volume is $0.5/0.5 = 1.0$. We refer to this ratio as the *top-down ratio*, or *t–d ratio*

$$v - h\ ratio = \frac{average\ height\ of\ vertical\ pyramids}{average\ height\ of\ horizontal\ pyramids}$$

$$t - d\ ratio = \frac{sum\ of\ top - pyramid\ volumes}{sum\ of\ bottom - pyramid\ volumes}$$

A person 170 cm tall, standing in a room of 2.5 m height, will have their vantage point (eyes) located above the room's centre yielding the *t–d ratio* lower than 1.[1] In the example case of a (very small) cube-shaped room with side length 2.5 m, the *t–d ratio* is calculated as

$$\frac{\frac{1}{3} \cdot 2.5 \cdot 2.5 \cdot (2.5 - 1.7)}{\frac{1}{3} \cdot 2.5 \cdot 2.5 \cdot 1.7} = 0.47$$

In most common everyday situations, human height above the floor is fixed and rooms are rarely lower than 2.5 m. Therefore, *t–d ratio* much lower than 1 is unusual, although such a proportion can be associated with the observer standing on an indoor balcony near the ceiling; this situation will be reviewed later. Moving into spaces with high ceilings, on the contrary, is associated with a growing *t–d ratio*. Consider a larger cube of dimensions $50 \times 50 \times 50$ m with a vantage point fixed at 1.6 m above the centre of its floor (see Figure 1(c) for a schematic representation). The *v–h ratio* in such a space also equals $25/25 = 1$, reflecting the fact that the perceived shape of the environment, and the relation between the accessible vertical and horizontal information, are the same as in the smaller cube. The *t–d ratio*, however, is

$$\frac{\frac{1}{3} \cdot 50 \cdot 50 \cdot (50 - 1.6)}{\frac{1}{3} \cdot 50 \cdot 50 \cdot 1.6} = 30.25$$

This reflects the perceived verticality of the larger space. Neither of these numbers change when the observer moves into the corner of the cube. Similar to the measurands proposed by Benedikt (1979) for 2D quantification, additional values can be obtained to reflect the position of the vantage point with respect to the boundaries of such a figure, e.g. based on the length and variance of distances to the isovist's boundaries. These are not explored in detail in the current article.

Jointly, the *v–h ratio* and the *t–d ratio* can therefore describe the shape of perceived space, while differentiating between horizontal and vertical information, as well as between the information visible upwards and downwards (Figure 1(b)). A space low and wide will have the *v–h ratio* much lower than 1, and the *t–d ratio* will depart from 1 as the observer's vertical position changes: the *t–d ratio* will grow if the observer has more information above, and will decrease when the observer is located closer to the ceiling. Conversely, a space which is narrow and high will result in the *v–h ratio* much greater than 1.

A common analytical scenario in architecture is patios with vistas opening into multiple floors or balconies. Consider a simplified environment presented in Figure 1(d). The proportion of horizontal information available to the viewer is limited, quantified as the relative volume of the horizontal pyramids. Therefore, the *v–h ratio* reaches a value comparable with a very tall but narrow space without such balconies. The environment presented in Figure 1 (d) has the dimensions of $40 \times 20 \times 20$, but its *v–h ratio* equals 2.6, derived for a person standing on the floor. A space without such balconies would need to have the dimensions of $40 \times 20 \times 78$ in order to achieve the same *v–h ratio*.

The next measure addresses this issue. Distinguishing between very high and narrow, but convex spaces and those which are low but have many vertical occlusions is possible with *vertical jaggedness*: a measure analogous to the inverse of *circularity* defined for the 2D case (Benedikt, 1979). This can be defined as the cubic root of summed vertical isovist volume, divided by the square root of the summed surface area of all upwards and downwards facing surfaces (Figure 1(e))

$$vertical\ jaggedness = \frac{\sqrt[3]{sum\ of\ vertical\ pyramid\ volumes}}{\sqrt{sum\ of\ vertical\ pyramid\ bases}}$$

Empirical evaluation: Predicting human perception of space with 3D isovists

In order to evaluate our 3D embodied isovist model in comparison with the generic volumetric 3D isovist model, we designed an experiment in which participants were asked to provide impressions about the surrounding space from multiple vantage points inside diverse building models. Inspired by the earlier findings of Wiener et al. (2007) and Stamps (2011), we asked participants to rate *spaciousness* and *complexity* of the experienced spaces. Inspired by the findings of Witt et al. (2007), we also asked participants to estimate the distance that separates them from a fixed target in space (a blue cube). The distance estimation data are not reported in this article but are available in the supplemental material.

Hypotheses

We hypothesised that the embodied 3D isovist properties will better correlate with the impressions of *spaciousness* and *complexity* compared to the generic volumetric 3D isovist measures.

Participants

Thirty voluntary participants (8 female and 22 male, aged between 20 and 30 years) were recruited from the local university. Each participant signed an informed consent form in accordance with the institute's ethical clearance policy. They were warned that the study takes place in a virtual reality setting which might cause nausea. It was emphasised that they are free to take a break or quit the experiment at any time.

Materials

The study was implemented in a virtual reality setting. Subjective impressions provided within virtual reality have been shown to correspond well with impressions that participants have in real architectural spaces (Kuliga et al., 2015) (but note that virtual reality has also been shown to produce compressed distance estimates (Renner et al., 2013)). We used SteamVR plugin and Unity 2018.2.4f1 to program the experiment. The camera in Unity that renders the scene was set to perspective projection with a vertical field of view of 60°.

Participants viewed the space through a head-mounted display HTC Vive Pro (resolution: 1440×1600 pixels per eye; refresh rate: 90 Hz; vertical field of view: 110°; horizontal field of view: 110°). They were free to move their head but were not allowed to walk.

Nine three-dimensional building models were created using SketchUp 2018 software. Between 1 and 3 vantage points were selected for testing within each building, resulting in 23 vantage points in total. They were chosen in a way that covers a broad spectrum of possible isovist shapes and sizes as well as corresponding spatial experiences. As we are interested in studying solely the effect of the buildings' geometry, the models had minimal windows, furniture, and ornamental features. All buildings, together with the selected vantage points, are presented in supplemental material 2. We developed a custom-built EmVis software tool within the InSpace3D framework (Schultz and Bhatt, 2013) and used this to calculate properties for both the embodied 3D isovist and the generic volumetric 3D isovist.[2]

Spaciousness and complexity rating tasks. Following the procedure used by Stamps (2011), we asked the question: 'Please rate on the criterion of how not spacious (1) and spacious (8) the building appears from your current position in the building' as well as 'Please rate on the criterion of how not complex (1) and complex (8) the building appears from your current position in the building'. In order to provide participants with common reference understanding of spaciousness and complexity, prior to the experiment, they were presented with images showing sample not spacious/averagely spacious/spacious, as well as not complex/averagely complex/complex architectural spaces. During the experiment, participants always heard the question verbally and also provided their rating verbally, on a scale ranging from 1 to 8.

Experimental design and procedure

The experiment followed a within-subject design: each participant provided responses to all three tasks, from all 23 vantage points. The order at which participants were shown each space was randomised. The randomisation algorithm included a rule preventing two vantage points from the same building to be shown directly after each other (at least two other vantage points would always be presented in between). This rule was implemented to prevent the participants from thoughtlessly carrying over the ratings from one vantage point to another, after realising that it is located in the same building.

After fitting and calibrating the head-mounted display, participants were shown a trial building. They were asked to verbally (1) provide the spaciousness rating, (2) provide the complexity rating and (3) perform distance estimation (see supplemental material 3 for details). After the trial, the procedure was repeated for all other vantage points, in a randomised order. Figure 2 presents sample views of the environments.

Results

Table 1 lists all vantage points presented to the participants, together with their corresponding isovist properties. We hypothesised that the *embodied 3D isovist* will be a better predictor of *spaciousness* and *complexity* than the *volumetric 3D isovist*, i.e. that using the *embodied isovist* predictors from Table 1 will improve the statistical explanation of participants' responses.

Statistically, this general hypothesis can be expressed as the model comparison problem: It is possible to construct alternative statistical models to explain *spaciousness* and *complexity* data which would differ by the selection of variables from Table 1 used as predictors. We constructed two types of such models: *volumetric isovist* models and *embodied isovist* models.

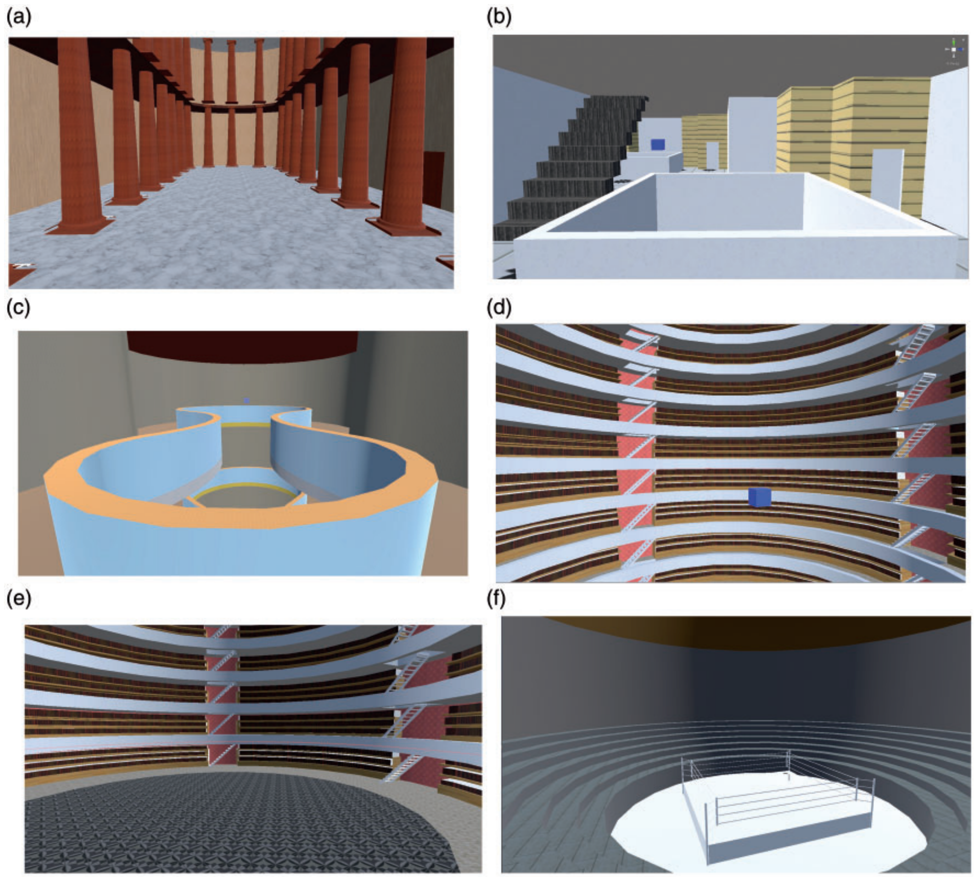

Figure 2. Views from the virtual building models, as they were seen in a head-mounted display by experiment participants. (a) Vantage point 'S' in building 'Pillared'. (b) Vantage point 'Q' in building 'Office building' during the distance estimation task (a blue cube is visible near the staircase). (c) Vantage point 'G' in building 'Eight shaped'. (d) Vantage point 'I' in building 'Library'. (e) Vantage point 'H' in building 'Library'. (f) Vantage point 'A' in building 'Boxing ring'.

Volumetric isovist models only included traditional *Volumetric isovist* predictors. *Embodied isovist* models additionally included as predictors new properties derived from the embodied 3D isovist presented in the previous sections. The question was, which of these alternative statistical models perform best in explaining the psychological data.

We implement Bayesian multi-level models (McElreath, 2018) in the brms R package (Bürkner, 2017), which is based on Stan (Carpenter et al., 2017). We interpret and highlight the effect of each predictor on the outcome variable as highly significant if its 95% Credible Interval excludes 0. All models contain a by-participant random intercept and random slopes. Therefore, models consider the fact that responses coming from each participant are likely to be correlated with other responses of this participant. Model comparison is conducted using the brms::loo_compare method. LOO greater than twice its standard deviation suggests that the model with lower LOO fits the data better – we highlight such differences as significant.

Table 1. Summary statistics for each vantage point from the study.

Building	Vantagepoint	Volume (vol)	Jaggedness (vol)	*v–h* ratio (emb)	*t–d* ratio (emb)	Vertical jaggedness (emb)
Boxing ring	A	3,828.80	0.43	0.81	8.61	0.44
Boxing ring	B	4,006.43	0.42	1.11	0.86	0.43
Column	C	70.11	0.40	1.09	0.78	0.45
Column	D	70.11	0.40	1.60	2.12	0.57
Column	E	70.11	0.40	1.60	0.17	0.57
Eight-shaped	F	5,243,788.80	0.43	0.74	11.45	0.47
Eight-shaped	G	5,774,624.00	0.43	0.89	0.34	0.46
Library	H	4,813.09	0.39	0.59	13.35	0.40
Library	I	4,994.24	0.37	0.63	1.13	0.38
Library	J	4,856.17	0.40	0.61	0.06	0.43
Long room	K	106,215.68	0.40	0.54	6.00	0.38
Long room	L	98,496.00	0.40	0.42	5.97	0.38
Long room	M	102,604.16	0.37	2.19	8.77	0.59
Long room	N	109,152.64	0.37	2.42	0.78	0.58
Long room	O	101,520.00	0.37	2.02	0.07	0.60
Office building	P	1,171.30	0.39	0.64	9.83	0.46
Office building	Q	1,302.59	0.38	0.98	0.26	0.45
Pillared	R	1,500.16	0.45	0.31	0.21	0.38
Pillared	S	2,133.81	0.47	0.37	0.96	0.49
Theatre	T	3,002.92	0.39	0.18	7.78	0.45
Theatre	U	3,141.58	0.39	0.31	4.87	0.33
X-shaped	V	96,219.52	0.39	0.55	10.24	0.44
X-shaped	W	79,009.28	0.44	1.48	0.22	0.60

The brackets in column names indicate whether a given variable was used as a *volumetric isovist* predictor '(vol)' or an *embodied isovist* predictor '(emb)'.

Compared to Table 1, we transformed some of the variables to facilitate model fitting: *volume*, *t–d ratio*, and *v–h ratio* were transformed using the natural logarithm; *jaggedness* and *vertical jaggedness* were mean-centred and standardised.

Predictors listed in Table 1 can be used to generate 30 alternative combinations. We tested all possible 30 combinations for each of the two dependent variables, implementing $30 \times 2 = 60$ models. For each dependent variable, we present the simplified comparison between the best-performing *volumetric isovist* model and the best-performing *embodied isovist* model. For reference, we identify each model with a unique numbered model name. For a complete comparison and description of all models, with their names and full formulas, please refer to supplemental material 4.

Spaciousness

Responses to the *spaciousness* and *complexity* rating tasks were modelled using the 'cumulative' model family (Bürkner and Vuorre, 2019). Raw results are presented in Figure 3(a). The model explaining the data best was 'spaciousness.emb.23'. It was also significantly better than the best-performing *volumetric isovist* model: 'spaciousness.vol.3' (Table 2). This demonstrates that the *embodied isovist* is a valuable predictor of participants' *spaciousness* ratings. The model explained 40% of variance in the data. Participants rated space as

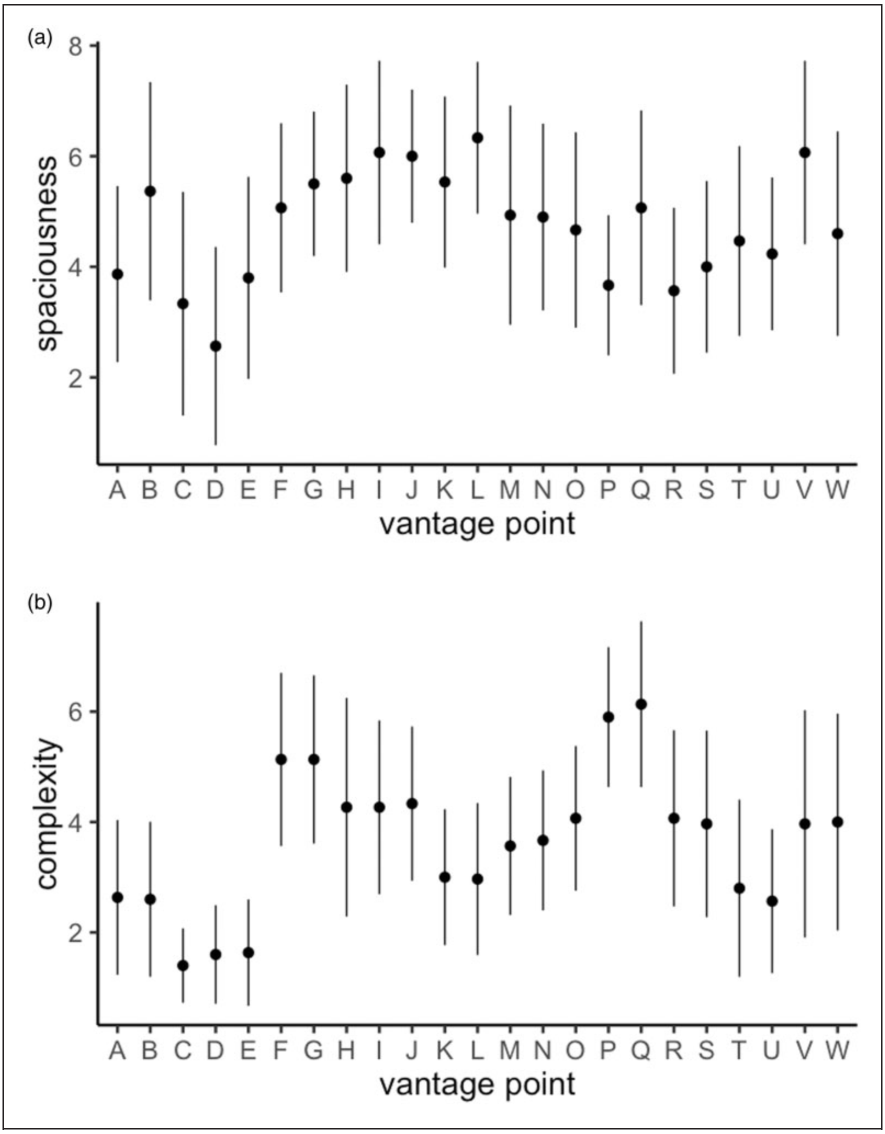

Figure 3. Raw data from (a) *spaciousness* rating and (b) *complexity* rating tasks. Dots represent mean result for each vantage point. Lines represent standard deviations.

more spacious if the vantage point had a larger *volume*, smaller *jaggedness*, lower *t–d ratio*, and smaller *vertical jaggedness* (Table 3).

Complexity

We repeated the procedure from the previous section to analyse the *complexity* ratings. Raw data are presented in Figure 3(b).

Model 'complexity.emb.21' explained the data best. It was also significantly better than the best-performing *volumetric isovist* model: 'complexity.vol.1' (Table 4). This

Table 2. LOOIC comparison of the best-performing *embodied isovist* model and the best-performing *volumetric isovist* model for the *spaciousness* rating variable.

Model name	LOOIC	ΔLOOIC	ΔSE	Sig.
spaciousness.emb.23	2481.82	0.00	0.00	
spaciousness.vol.3	2535.64	–26.91	8.09	***

For a full formula of each model, refer to its name in supplemental material 4.
Significance marked with '***' when the 95% CI excludes 0.difference in LOOIC (second column) is larger than twice its Standard Error (thrid column).

Table 3. Posterior mean estimate, standard error and 95% credible interval for each parameter of model 'spaciousness.emb.23' with a varying intercept and varying slopes by participant.

Predictor	**Estimate**	**SE**	**95% CI**	**Sig.**
Intercept[1]	–1.42	0.39	[–2.19, –0.63]	***
Intercept[2]	–0.25	0.37	[–0.97, 0.52]	
Intercept[3]	1.23	0.37	[0.53, 2.01]	***
Intercept[4]	2.43	0.38	[1.70, 3.24]	***
Intercept[5]	3.38	0.39	[2.64, 4.20]	***
Intercept[6]	4.52	0.40	[3.75, 5.36]	***
Intercept[7]	5.76	0.42	[4.98, 6.65]	***
volume (log)	0.28	0.04	[0.21, 0.36]	***
jaggedness	–0.45	0.08	[–0.61, –0.29]	***
t–d ratio (log)	–0.16	0.04	[–0.25, –0.07]	***
vert. jaggedness	–0.58	0.09	[–0.75, –0.41]	***

Significance marked with '***' when the 95% CI excludes 0.

Table 4. LOOIC comparison of the best-performing *embodied isovist* model and the best-performing *volumetric isovist* model for the *complexity* rating variable.

Model name	LOOIC	ΔLOOIC	ΔSE	Sig.
complexity.emb.21	2478.13	0.00	0.00	
complexity.vol.1	2513.10	–17.49	5.73	***

For a full formula of each model, refer to its name in supplemental material 4.
Significance marked with '***' when difference in LOOIC (second column) is larger than twice its Standard Error (third column).

demonstrates that the *embodied isovist* is a valuable predictor of participants' *complexity* ratings. The model explained 32% of variance in the data. Participants rated space as more complex if the vantage point had a larger *volume*, smaller *jaggedness*, smaller *v–h ratio* and smaller *t–d ratio* (Table 5).

Lastly, we considered the possibility that other isovist measures (untested here) might have a significant impact on spaciousness and complexity ratings. This analysis demonstrated no impact on our conclusion and it is presented in supplemental material 5.

Discussion

We presented a user study investigating a cognitively motivated extension of the 3D isovist. Results of the empirical experiment consistently demonstrated that the embodied 3D isovist

Table 5. Posterior mean estimate, standard error and 95% credible interval for each parameter of model 'complexity.emb.21' with a varying intercept and varying slopes by participant.

Predictor	Estimate	SE	95% CI	Sig.
Intercept[1]	0.46	0.34	[–0.21, 1.13]	
Intercept[2]	2.06	0.35	[1.39, 2.77]	***
Intercept[3]	3.21	0.36	[2.53, 3.92]	***
Intercept[4]	4.10	0.37	[3.4, 4.84]	***
Intercept[5]	4.78	0.38	[4.06, 5.54]	***
Intercept[6]	5.90	0.41	[5.12, 6.71]	***
Intercept[7]	7.27	0.46	[6.4, 8.22]	***
volume (log)	0.31	0.03	[0.25, 0.37]	***
jaggedness	–0.21	0.08	[–0.37, –0.05]	***
v–h ratio (log)	–0.64	0.13	[–0.9, –0.4]	***
t–d ratio (log)	–0.23	0.05	[–0.32, –0.14]	***

Significance marked with '***' when the 95% CI excludes 0.

is a more reliable predictor of the human perception of space compared to generic volumetric 3D isovists. Statistical models including the newly proposed measurands outperformed statistical models based on the generic volumetric 3D isovist calculations. In our study, participants' ratings were correlated not only with already known predictors of *spaciousness* and *complexity* (*volume* and *jaggedness*) but also with *t–d ratio*, *v–h ratio* and *vertical jaggedness*, indicating that human occupants are sensitive to the asymmetries between the amount of space visible above and below them, as well as the asymmetries between the amount of space visible horizontally and vertically.

This extends the existing body of knowledge on the perception of *spaciousness* and *complexity* that has traditionally been studied from a fixed height above the surface of a floor or street level (Stamps, 2011; Wiener et al., 2007). Architects might consider these biases in human perception when designing multi-level buildings: it cannot be expected that the visitors' experience will be similar at all floors of the building, even if their layout is identical. Occupants are likely to feel that the building is more spacious if (keeping other things equal) they were located higher (i.e. experienced a 3D isovist with lower *t–d ratio*) and saw space that is less vertically jagged (cf. Figure 1(d)). Building users are also likely to feel that the space is more complex if (keeping other things equal) they were located higher and in a space that is wider than taller (i.e. experienced a 3D isovist with lower *t–d ratio* and lower *v–h ratio*).

Our findings add to the growing body of evidence supporting the embodied nature of the architectural experience (Jelić et al., 2016; Mallgrave, 2013; Waller, 2014). This aligns with earlier work emphasising explicit links of Space Syntax methods with human perception and cognition (Conroy Dalton, 2005; Penn, 2003). The empirical validation of the embodied 3D isovist model extends the logic behind, and the practical aim of, the original isovist: to describe spatial information relevant to a potential human occupant of space.

Our contribution goes beyond the traditional one-to-one mapping of correlations between a spatial measurand and a psychological response, by testing 30 combinations of predictors (statistical models) and selecting those that perform best in predicting the human-generated data. The presented method makes it possible to select a subset of measurands that combines a high predictive power with a low number of predictors. This has practical implications when one is interested in predicting the potential perception of space with a limited number of isovist measurands: a smaller number of measurands is easier to control and manipulate during the design process. Finding combinations of isovist measurands that are simple but effective is therefore an important practical challenge that determines the potential usefulness of the described methods in the design practice.

In his review of the contribution of Space Syntax to environmental psychology, Montello (2007) points to limitations of isovist analysis. Applying a 'one-size-fits-all' visibility representation falls short of accounting for known contextual and interpersonal differences in perception of space. In this paper, we argue that accounting for direction is one of the required building blocks for a concept that Montello calls 'weighted' or 'probabilistic' isovists – a representation that not only conveys what is possible to see, but what is likely to be seen (by differing groups, in differing contexts).

Related work

Isovists as predictors of human perception

Researchers studied whether isovists can explain human subjective impressions of visible space from a single vantage point. Stamps (2009, 2011) conducted a series of experiments in which participants were asked to rate streets and buildings for perceived spaciousness, in static and dynamic virtual simulations. He found that horizontal area is the strongest predictor of spaciousness ratings and that street views of the same total area can be rated differently, depending on their particular shape (Stamps, 2011). In his earlier work, Stamps linked isovist properties with perceived enclosure (Stamps, 2005) concluding that area and jaggedness (which he terms *concavity*) are the most plausible variables for uniquely describing isovists and correlating them with perceived enclosure.

Wiener et al. (2012), and later Emo (2014), demonstrated that the geometry of architectural space visible from a single vantage point also explains the preferred choice between two alternative routes, as well as the eye movement of navigators perceiving these alternatives. The analysis demonstrated that vertical information, mostly containing floor and ceiling surfaces, was only sparsely explored by the navigators.

Isovist implementations: 2D, 2.5D and 3D

Methods to model the extent of space visible from a pre-defined vantage point were developed within two different disciplinary perspectives: as 'isovists' in the architectural context, and as 'viewsheds' in landscape planning. Despite isovists and viewsheds being considered as three-dimensional on a conceptual level, their early computational implementations were two-dimensional.

Limited by the availability of three-dimensional data, researchers utilised digital elevation models in 2.5-D visibility analysis. This approach only accounts for a single z-value for each xy-coordinate, limiting its applicability in architecture: inside buildings, a single wall can have many openings such as holes or balconies. Bishop (2003) and Llobera (2003) provide a review of 2.5D visibility models.

The availability of new methods for sampling and storing three-dimensional data (e.g. Building Information Modelling and LiDAR) accelerated work on three-dimensional isovist implementations. Derix et al. (2008) presented a set of methods for calculating three-dimensional visibility inside architectural spaces. Based on the idea of the visibility graph (Turner et al., 2001), these methods quantify the changes in how open or constrained the space might seem to a potential navigator. Lonergan and Hedley (2015) provide a review of recent approaches to modelling three-dimensional visibility.

Considering the type of space belonging to an isovist, Fisher-Gewirtzman (2016) presented a 3D visibility model which accounts for the semantic property of visible parts of the urban environment, such as roads or trees. Dalton and Dalton (2015) considered the challenge of representing 3D isovists, which becomes especially problematic when different subregions and the semantic content of the visible space is of interest.

Varoudis and Psarra (2014) extended the traditional visibility graph approach to the third dimension by accounting for accessibility affordances of floors. Their approach begins with defining ‘accessible’ and ‘inaccessible’ spaces in the layout, which are represented as a three-dimensional grid of isovist vantage points (for a similar approach, see Lu et al., 2019). A ‘mixed’ visibility graph consisting of undirected and directed edges is then generated. Classical ‘undirected’ edges are created between nodes representing locations which can serve both as origin and as destination of a potential observer ‘looking out’ towards the other node; ‘directed’ edges represent connections between two spaces, of which only one can serve as a potential destination. This can reflect a situation when the observer looks at a void, high in the air above the floor’s surface. This approach goes beyond a simple generic *volumetric 3D isovist* and considers spatial properties relevant to the human movement. As demonstrated by Lu and Ye (2019), this 3D visibility model has clear advantages in representing human cognition, compared to a 2D isovist equivalent, especially in the context of multi-floor buildings. However, it treats void spaces above and below the vantage point as equally accessible, and gives equal weight to vertical and horizontal information.

Limitations and conclusion

The paper demonstrated the validity and advantages of the embodied 3D isovist in accounting for the perception of space of building users.

Both the computational implementation of the concept and its empirical validation are limited and deserve further work. Firstly, the current paper considered only a case of a single vantage point and did not describe the relations between individual vantage points, as it is customary in the Visibility Graph Analysis (Turner et al., 2001). By providing the computational definition of the embodied 3D isovist, we hope it can be extended to the graph-based configurational analysis of visibility in space. Furthermore, although participants in the present study could look around in the VR environment they were positioned at a stationary location, and thus *locomotion* in combination with visibility was not considered, e.g. in contrast to drift analysis (Conroy Dalton, 2001) and visuo-locomotion studies (Bhatt et al., 2016; Kondyli and Bhatt, 2018; Kondyli et al., 2017).

Secondly, the impact of colour and lighting on the elicitation of spaciousness and complexity was not taken into account. Numerous studies have demonstrated the impact of colour on subjective impressions of interior environments (Flynn et al., 1979; Yildirim et al., 2011).

Lastly, our embodied 3D isovist treats space to the left and to the right of the occupant as equivalent. It bears noting that in some contexts this assumptions is not true: people’s handedness has been linked to the judgement of positively versus negatively associated locations in space (Brunyé et al., 2012). Similarly, our model does not distinguish between the space in front and behind the occupant, which is an important aspect of how people perceive space (Montello, 2007; Tversky, 2009). Our presumption is that these effects are less important in the cumulative judgement of a building’s *spaciousness* and *complexity*. However, the provided method of deriving embodied 3D isovist properties is easily extendable from the *t–d ratio* measure, to one that could account for the left/right and front/back asymmetries in the visible space, after accounting for the orientation (looking direction) of the user.

[1]One might be tempted to consider the relationship between the volumes of vertical and horizontal pyramids. However, this does not usefully reflect the shape of an environment. For example, in a unit cube the ratio of the volume of vertical and horizontal pyramids is $2/4 = 0.5$. If we vertically stretch the cube into a tall rectangular cuboid then we might expect this ratio to increase, reflecting greater vertical information. However, the proportion of horizontal pyramid volume to vertical pyramid volume stays the same. This is because, while the height of the vertical pyramids increases, so does the surface area of the walls (i.e. the base of the horizontal pyramids).

[2]The EmVis software tool, as well as the dataset and all supplemental material, are available for download from https://osf.io/qvkwz/.

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