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Unravelling the Progressive Gallery Paradox

Behaviour analysis in an art gallery typology through neuroscience and morphology

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ABSTRACT

Concentrating on visitors' spatial behaviour, this study investigates the 'progressive gallery' (PG), an exhibition space typology with sequential arrangement of rooms. Resulting from a doctoral thesis, it bridges space syntax and neuroscience. The impact of PGs on the function of attention is evaluated by computing the response of focus in visitors navigating virtual galleries. The initial hypotheses were: visual fields in PGs are highly intelligible; deterministic layouts lead to more focused visitation experiences, and architectural space has great impact on museum visitation, particularly when trajectories are limited. The overall research departed from analysis of simple hypothetical matrixes and pre-twentieth century gallery layouts, and two emblematic PGs, the Solomon R. Guggenheim Museum and the Museum of Unlimited Growth. It then evolved to analysing complex PG variations, lastly including visitors' path tracking and capture of focus during immersive virtual reality navigation in such layouts, the focus of this paper. The "Degree of Progression" and the "Index of Variation of Peaks of Focus" are introduced. The first relates to spatial progression through associations with syntactic measures and the second quantifies the variation of focus during visitation. After comparing real visitors' paths and responses of focus with results from syntactic analyses, a close relationship between spatial geometry and neural responses was observed, which may provide valuable data for curatorial and architectural projects. Findings showed that the coexistence of intelligibility, good intervisibility of fields and a route-defining geometry, contrary to hypothesis, did not necessarily lead to highly focused visitation experiences, revealing the PG paradox.

KEYWORDS

Spatial cognition, Museum studies, Neuroscience and architecture, Space syntax, Virtual reality

1 INTRODUCTION

In previously published work we discussed the concept of the progressive gallery (PG) as a type of exhibition space with origins back in the 16th century that emerged after the French Revolution. The PG's seminal morphological matrix presented sequential spatial units in a row, formally aligned with each other, guiding visitors through a space, as a rule, elongated, with works of art arranged along its walls that facilitated the continuous movement and viewing of the exhibited pieces, regardless of additional visual resources (Bennett 1995, p.76; Sutton 2000, p.23). Triggered by two emblematic cases - the Solomon R. Guggenheim Museum (GM) and the Museum of Unlimited Growth (MUG) – these former studies examined to what extent the arguably deterministic configuration (Choi 1997) of PG layouts would interfere on the visiting experience in regard to encouraging visitors to explore the space while strengthening its social nature (Rolim et.al 2017, Rolim et.al 2018).

We have showed that in the GM, especially after renovations to the original design by Frank Lloyd Wright (1943-1959), the high-ceiling rotunda wrapped by ramped galleries promoted a very different spatial experience than that in the adjacent (and non progressive) exhibition spaces. While the rotunda space was introspective and highly controlled trajectory-wise, its social nature was strong. On the other hand, Le Corbusier's design for the MUG (1939), with exterior openings at each axis of its spiralling sequential galleries offered a freer exploration and several possible trajectories. In addition, the drastic changes in visual fields we assessed through spatial analysis seemed to facilitate a richer experience when compared to the GM (Rolim et.al 2018). These earlier studies included computational syntactic analysis and on-site observations, helping to set the basis for a PG matrix, which we sought to establish based on further investigations including agent-based simulations in hypothetical layout variations. Borrowing metrics and configuration from the GM's rotunda and the MUG, these variants started as a long and narrow PG, first with straight walls that became sinusoidal, chamfered and niched. Further testing its progression, the gallery gained aggregate cells off the main space, similar to the GM after the annex by Gwathmey Siegel and Associate Architects was added in 1990s (Rolim et.al 2019). Throughout the development of the doctoral thesis (Rolim 2020) that originated this paper, hypothetical PG layouts were examined, GM and MUG evaluations improved and historical PG galleries were also analysed.

The thesis' research questions were: Would it be possible to reconcile the deterministic nature of PGs with a exploratory visiting experience? Would the progressive condition strengthen the social nature of the space while providing an intelligible navigation with a good response of focus from visitors, or would these be irreconcilable paradoxical conditions? Relying on the interface between neuroscience and architecture to help addressing these issues, the former can inform about the specific cognitive experiences generated by the human brain in built environments, complementary to the knowledge about movement and visual fields informed by space syntax (SS). Our interest in neuroscience lies in the human response of focus, understood as a measure of fixed attention for a specific task, indicating the level or depth of this attention (Radek 2011, Menon 2015).

We will concentrate on the morphological analysis of hypothetical gallery layouts and the relationship between these and EEG-based experiments in immersive VR, which included navigation in three types of sinusoid PGs (single (S), double symmetric (DS) and double asymmetric (DA)) with and without works of art (Figure 1). The theoretical basis will follow next, then the datasets and methods, finalizing with presentation of main results and conclusions reached.

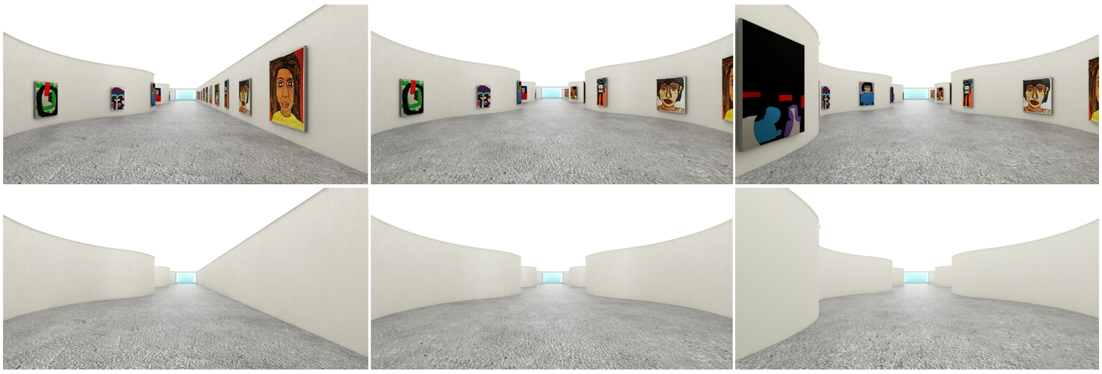

Figure 1: Single, double symmetric and double asymmetrical sinusoid galleries with (top) and without (bottom) works of art used in VR and neuroscience-based experiments.

2 SPACE SYNTAX AND NEUROSCIENCE: THEORETICAL BASIS FOR AN INTERFACE

Situated within the field of neuroscience-informed design, this research relates to investigations regarding the subject-environment relationship. The greater knowledge of our neurological map, chemical and synaptic system in the last 30 years has transcended the hard sciences, starting to be translated into the human sciences (Mallgrave 2013a). The approach to the biological sciences in psychology of aesthetics and art research in the 19th century coincided with the beginning of the modern tradition in neuroscience to observe, manipulate and measure, which allowed scientists to start determining how the brain actually worked (Gazzaniga et.al 2014, p. 5).

Important advances in biological sciences and neuroscience occurred from the 1990s onwards, such as the discovery of the brain’s DNA genetic sequence (2003) and functional magnetic resonance imaging (fMRI), facilitating internal visualization of the brain in activity and further studies in microbiology and neurology that have eased the assessment of human responses to environmental stimuli (Mallgrave 2013b, p. 10).

Previously considered a subdivision of biology, neuroscience is currently defined as an interdisciplinary science that supports several empirical disciplines (experimental psychology, cognitive science, chemistry, anatomy, physiology and computer science), focusing on the relationships between brain and behaviour, which it investigates through its internal human processes, such as sensation, perception, cognition, memory and emotion (Albright, 2015). According to Eric Kandel, before a systematic brain science emerged in mid-twentieth century, “researchers relied on psychology and on the emerging understanding of visual perception to investigate the workings of the human mind” (Kandel 2016, p.17). Nowadays, there is greater biological knowledge and tools for gauging aspects previously tested theoretically or with less precision. This relates to the connection between neuroscience and architecture in 1960s, when behavioural sciences emerged as an influence to the latter and the theory of the social logic of the space (Hillier and Hanson, 1984), clearly stated in its inaugural publication: “the syntactic theory is used to integrate a number of recent propositions made in anthropology regarding human space organization” (Hillier et.al 1976).

The central SS argument was that morphology might be generated from a careful set of basic objects, relations and operations, which combined would conform the syntax. This would enable the understanding of characteristic patterns of buildings and cities, informing about the objective similarities and differences that a set of phenomena exhibit to common experience. Therefore, the strongest link between SS and neuroscience is their common interest in human behaviour. Numerous studies in SS have been developed through gradually expanding methods, leading to investigation of new topics, such as cognition, perception and, more recently, neuroscience. According to Hillier and Tzortzi (2011), museum studies in SS began as early as 1982 and encompass several areas of interest, including those about the space and observer and the space and cognitive function, which share an interest with cognitive neuroscience. The authors provide a review of works about culture of space and visitation by Psarra and Grajewski (2000), Psarra and Grajewski (2002), Psarra (2005), which together with the more recent publication by Psarra (2018) were relevant to this research. Works on behavioural and cognitive functions in exhibition spaces by Peponis (1993), Peponis et al (2003) and Stavroulaki and Peponis (2003) are other important references.

Tzortzi (2015) suggests that the understanding of how circulation is configured in a layout has been recurrent in museum studies, unfolding in four key themes, adopted as overall guidelines on this research: how spatial arrangement in sequential galleries relates to the way people move and explore galleries; the intelligibility of the layout; the visualization of objects and how the museum works as a social space.

Regarding experience, SS studies have pointed out that cities and buildings are structured to make the physical movement of bodies efficient and intelligible to minds (Hillier 2003). Thus, the concept of intelligibility (R2), key in our investigation, refers to easing or troubling the way we understand the shape of a space from the view we have, one at a time, of a part of this space, when we move there.

As for SS studies in cognition, the model and simulation techniques with automata agents created by Alasdair Turner and Alan Penn (Turner and Penn, 2002; Turner, 2003, 2007a and 2007b) are of particular interest to our study. Helping to understand the natural visual interaction between the individual and the environment, it focused on connections between mutually visible locations in a setting, generating aggregate levels of motion similar to those found in real environments. Dalton et al (2015) specifically supported areas of synergy between neuroscience, cognitive science, and SS. They acknowledged that each had a different scale of concern (the societal-like focus of SE, the individual-level focus of cognitive science, and the micro scale of neurons examined in neuroscience), encouraging collaborations amongst these fields by suggesting four research areas: acquisition of spatial information, the role of orientation in wayfinding, multi-story environments, and navigation and intelligibility. Our research concentrates on the latter. Within cognitive neuroscience, our approach is based on the measure of focus and originates from the understanding of human cognition as a result of interactions between specific neural networks, one of which is the salience network (SN), directly involved in human responses to experience in space.

2.1 Notes on Cognitive Neuroscience and the Focus of Attention

Cognitive neuroscience (CN) aims to understand how "the functions of the physical brain can produce the thoughts and ideas of an intangible mind" (Gazzaniga et.al 2014, p. 4). Its central question is how the mind is activated by the brain as a whole or by specialized parts, operating with relative independence. CN examines perception, language understanding, memory, problem solving, as well as decision-making and attention, the aim of our experiments.

The notion that human cognition results from interactions between specialized brain networks is widespread in neuroscience. The salience network (SN) is a large-scale network located at the interface of cognitive, homeostatic, motivational and affective systems of the brain. It has a crucial role in identifying endogenous and external stimuli, which are relevant, biologically and cognitively, and in guiding behaviour. The SN contributes to a variety of complex brain functions, including communication, social behaviour and self-awareness through the integration of sensory, emotional and cognitive information (Spreng et.al 2013; Menon, 2015; Ashwal, 2017).

Two antagonistic circuits are connected to the SN: the default mode network (DMN) and the dorsal attention network (DAN), that, in turn, connect to a third circuit, the Executive Control Network (ECN), which is able to couple to other networks. The DMN suits cognition internally, with greater activity during the resting state. The DAN is thought to be responsible for extrinsic awareness, orienting the individual's focus to a specific task. The ECN handles goal-directed cognition, helping the first two with eye movement, filtering stimuli and changing and orienting attention (Spreng et.al 2013, Li et.al 2014, Gazzaniga et. al 2014, p. 275). (Figure 2)

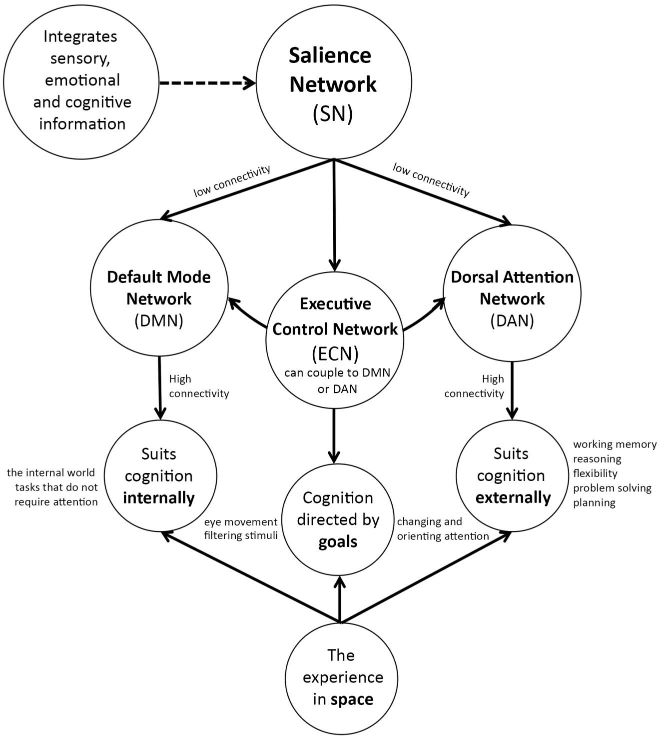

Figure 2: Salience Network (SN) diagram.

Attention phenomena are diverse and involve many computations and mechanisms of the brain that may provide a better description of how a healthy brain works and reveal how to improve attention deficits. This type of knowledge can also be applied to a better understanding of human responses to the built environment.

Our approach centres on the measure of attention of focus and departs from the understanding of human cognition resulting from interactions between specific neural networks, including the SN, which is directly involved in responses to experience in space. To do so, we associate such measure with SS analysis of movement and vision of visitors navigating virtual PGs.

3 DATASETS AND METHODS

We examined visitors' behaviour in three types of gallery layouts by tracking their paths, observing their fields of vision and responses of focus during immersive VR navigation, to compare these with agents' behaviour obtained from computational SS analyses.

Regarding the latter, the global and agent parameters used in the agent analysis (Turner and Penn 2002) were adjusted based on VR tests, including: 75cm x 75 cm grid (average length of an adult human step); one entrance at the narrow end of the main gallery (on left-hand side of floor plans); 12 step-average prior to agents changing path direction; and total visitation time of 186 timesteps (with .5 sec / step), which relates to the average time (93 seconds) spent by visitors in VR navigation. Simulations with both 20 and 10 agents (same as in VR tests) were carried.

All (10) participants in the VR experiments were male and female architecture and urban planning students, aged between 18 and 28. Brain-Computer Interface (BCI) wireless headsets (Insight 5-Channel Mobile EEG) were used for electrophysiological monitoring of the activity of the brain and, for capturing the VR experience, a set of Oculus Rift + Touch Virtual Reality System VR goggles and hand-held joystick. Additional equipment was handled by the researcher, including two floor sensors (Oculus Sensor), a laptop, and a cell phone with the EmotivBCI application, connected via Bluetooth to the participant's headset.

Developed by Emotiv, this application considers the measure of focus for a specific task that quantifies the depth of attention, as well as the frequency with which it switches between tasks, so that a high level of exchange of tasks is an indication of lack of focus and distraction. It allows us to visualize and train four types of data streams: mental commands, performance metrics, facial expressions and motion sensors. Data streams for performance metrics are shown at the frequency rate of 0.1 Hz, which enables passive and continuous control based on the subject's cognitive state in real time and to evaluate focus (our goal), excitement, interest, engagement, stress and relaxation. The algorithms for measuring these metrics (or cognitive states) generate results on a scale of values from 0 to 100, represented in a graph that relates them to the response time (Emotiv, no date).

The experiments took place in an air-conditioned classroom, with adequate artificial and natural lighting, measuring 7m x 10m, with a ceiling height of 3m, from which an area of 4m x 4m, free of obstacles, was used for navigation. In VR the height of the camera was programmed to be adjustable to the user from the floor height of 0.00m and the angle of view set at 90 degrees. Revit (Revit, 2017) was used for basic 3D models and Unreal Engine 4 (Unreal Engine, 2019) for final modelling and capture of real-time VR navigation.

Before starting to browse the three galleries, each participant was subjected to familiarization with the devices and instructed to navigate freely in each gallery for as long as they deemed necessary to visualize the entire space. Between one gallery and another, there was a neutral outdoor environment for resting as needed. Upon reaching this space, after leaving a gallery, it was left up to the participant to remove the goggles or not and spend as much time as they thought necessary before entering the second, and then, the third gallery. While five volunteers visited sinusoid galleries with works of art (GwA), the remaining five subjects navigated in galleries without art (GwoA), computing 30 layouts total.

3.1 The morphology of the galleries

In previous work we detailed how PG layouts resulted from historical galleries, the GM and the MUG. This base model started from inscribing different permeability levels to a purely progressive system. Through deformation of its limiting barriers or addition of new spatial cells, the system became more complex, altering its progressive condition (Rolim et.al 2019).

With artefacts exhibited on its longitudinal walls (in shallow niches or, more often, without them) and no other visual resource besides its own geometry, the "pure" configuration would contribute to the engagement in an uninterrupted path through a single space sequence. This relates to Bill Hillier's argument that linear spaces are interesting as predominantly elongated shapes that increase the focus of vision to cover a greater distance (Hillier, 2003).

The proposed morphology followed a simple logic. A purely progressive layout, with uniaxial, uniconvex space enabling a wide visual field, gained niched-spaces directly adjacent to it and was changed transversally (deformation of limiting walls) and longitudinally (shifting of limiting walls), which transformed the configuration into a multi-convex spatial system.

The longitudinal displacement and asymmetric folding of the cavities turned visual information about adjacent spaces less available, making it difficult for visitors to explore the space peripatetically, when "appreciation angles of the architectural form, the spatial continuum and the visual integration" (Amorim 2012, p.35) would possibly enhance the logical understanding of the gallery. Little by little, these adjacent spaces expanded the multi-convexity of the systems, becoming more hermetic by gaining a network of aggregate spatial cells (ASCs), more or less articulated with each other, until forming perhaps a separate spatial system. (Figure 3)

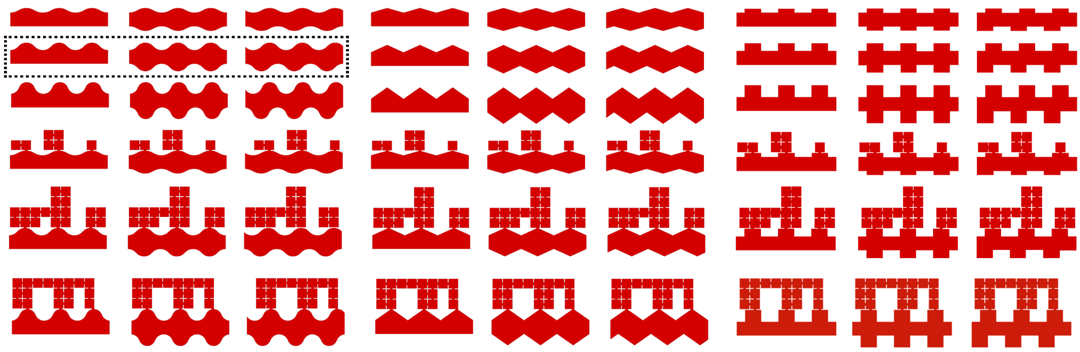

Figure 3: Sinusoid, chamfer and niche layout variations, highlighting those also tested in VR experiments.

3.2 Interior and exhibition design

The galleries were designed with neutral materiality and ambient lighting, with one window directly opposite the entrance, in the gallery's narrow end. The flooring was in epoxy-coated concrete, and walls and ceiling painted in white colour with matte finish. All 23 paintings exhibited were by North American artist Sadie Benning, whose work focuses on themes of masculinity versus femininity and the challenges of being young. In addition to using the same medium, the collection was chosen due its figurative nature, depicting characters in bright colours that would perhaps be easily assimilated by visitors.

Prioritizing placement of art over its content, the works were organized around a central axis, according to the positioning of predominant tones, following compositional models by Hilla Rebay, the first director of the Solomon R. Guggenheim Foundation, expressed in her (undated) sketches "How to hang a painting" (Vail 2009, p.42). Rebay favoured works of different proportions, emphasizing as guidelines: to maintain a central position in the display; to use colours that harmonized with each other; to place paintings at low heights (as this was less eye tiring) and bottom-aligned with each other, and to carefully select the works, avoiding the *pot pourri* effect. (Figure 4)

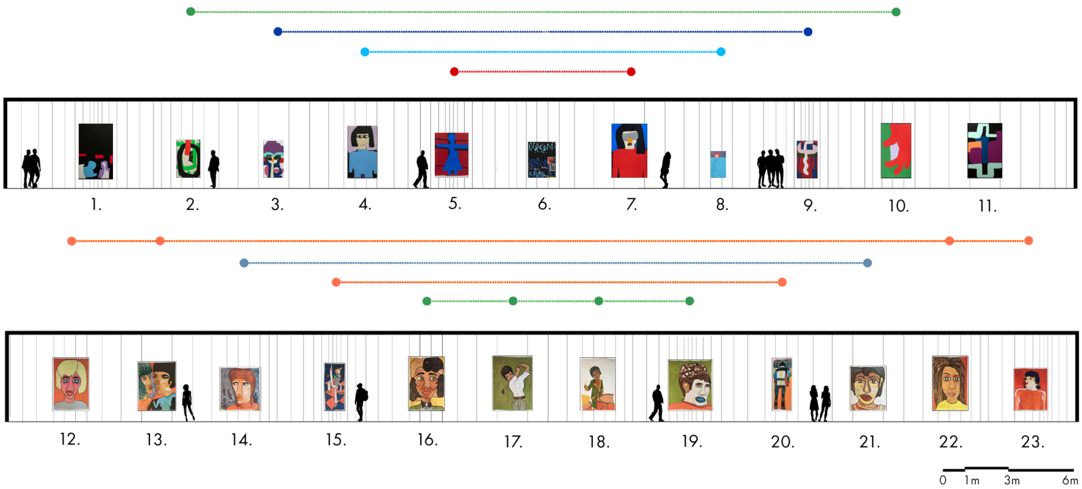

Figure 4: Exhibition design in main gallery with works by artist Sadie Benning.

4 RESULTS

Prior to presenting the results of VR and EEG-based tests, we will address the main findings from the syntactic analyses to later contrast these with the virtual experiments.

4.1 The Syntax of PGs

Our main goal is to assess the Degree of Progression (DoP) in PG layouts based on associations to the syntactic measures of Relative Connectivity (RC), Mean Depth (MD), Integration (HH), Intelligibility (R2), and Visual Connectivity (VC), approached through convex and visual graph (VGA) analyses of 54 layout variations. We also conducted agent-basis analyses of gate counts and trail maps, crucial for comparison with VR experiments.

We will focus on aspects considered particularly supportive in addressing the research goals regarding PGs: to investigate the relationship between layouts and patterns of exploration by visitors, to measure intelligibility and to evaluate to what extent this condition favoured the museum as a social space.

4.1.2 Convex and VGA analyses

A key SS property, connectivity (C) accounts for the local relationships of adjacencies in between neighbouring spatial units, establishing that two spaces are adjacent when one can be accessed directly from the other. Due to the controlled parameters of the layouts (e.g., main gallery connected to 3-6 cavities), the degree of C was similar in galleries without ASCs, varying from 2 to 3, with the following average values per family: C=2.44 (sinusoid); C=2.66 (chamfer);

C=2.66 (niche). Although the number of convex spaces increased in galleries with ASCs, connectivity remained within the same range (2 – 3).

The measure of RC is relevant for spatial systems of different sizes, as in our sample. It associates the number of convex spaces with other variables, such as the number of circulation rings and, according to Amorim (1999) can be expressed as RC= c- (p-1) / 2p-5, where "c" represents the number of connections and "p" the number of convex spaces. RC values vary from zero (in a tree-like graph) to 1 (maximum value).

Due to the defining role of the main gallery, in general, the justified graphs showed predominantly tree-like structures, such as the cases of all layouts without ASCs (RC =0). In galleries with ASCs, RC values increased, reaching a maximum of 0.17 and a minimum of 0.04, showing that, even with additional cells, RC values remained low.

For the same reason, the average mean depth of all layouts without ASCs was low (MD=1.63). In cases with added cells, this average increased slightly (MD =1.98). Considering all layouts by family shape, the average MD was 1.8. Thus, ASCs did not affect MD values significantly; perhaps a positive aspect for exhibitions, such spaces would involve short syntactic distances. Visual connectivity (VC) computes the number of visible spaces from another space, counted according to the placement of the isovist field of each space over the layout and identifying the spaces overlapped by such isovist (Benedikt 1979, Tzortzi 2015, p.117). Observing all 54 variations, the degree of VC decreased in all families when layouts gained ASCs and formed one or more circulation rings (Hillier and Tzortzi 2011). Lower average CV values occurred in galleries without ASCs, as following: 1.5 (single deformation), 2.5 (double symmetric and asymmetric). The highest values amongst galleries with ASCs varied from 3.0 (single deformation and shallow cavities) to 7.0 (double deformation and deep cavities).

Contrasting C and VC in all layouts, higher values remained in the main gallery. In general, the increase in C and VC did not always correlate. Inversely, outside the main gallery (in ASCs) VC only increased when permeabilities were simultaneously aligned with the vertical axis of main cavities and with the horizontal axis of ASCs in a row. Thus, more likely, visitors would see and be seen and would visualize the exhibition within those spaces from other spaces, and vice-versa. Intelligibility (R2) is a correlation coefficient between the local attribute of C and the global measure of integration (HH), helping to identify how easy it is for a visitor in a local position of a given spatial system to understand its global structure (Conroy 2001). Convex analysis revealed that almost half of all layouts (46%) showed a perfect correlation (R2=1.0) that occurred in galleries without ASCs, including 2 cases with highly pronounced values (0.90 and 0.99).

Very low values (R2=0.17) were recurrent in all family variations with deeper cavities and unilateral wall deformation, as well as in the medium double niche symmetric gallery with ASCs.

In general, there were not abrupt differences in R2 values per family. Nevertheless, considering only galleries with ASCs, R2 varied mildly when contrasted with types of deformation and cavity depth (shallow, medium and deep) pointed to more variation in the former than the latter. Thus, the intelligibility in more complex PG layouts (with ASCs) was mostly affected by the shape and positioning of limiting walls – unilateral, bilateral symmetric or bilateral asymmetric - than the depth of cavities within such barriers.

As a whole, average R2 values in all families were pronounced, with almost identical values: R2=0.70 (sinusoid); R2=0.74 (chamfer); R2=0.73 (niche). Hence, we argue that visitors could easily navigate these layouts. Since galleries without ASCs (with more progressive layouts) clearly presented higher R2 values than those with ASCs, we confirmed one of our initial hypotheses: the more progressive, the more intelligible a layout is when it comes to physical permeability.

As for VGA analyses, the main goal was to examine to what extent the galleries were visually intelligible, which required to first analysing visual integration (HH) and VC in layouts.
HH measures how many fields of vision a visitor would have to take into account to see the entire spatial system or, as put by Hillier (2003), the informational effort required to see all points from all other points. When we contrasted HH values in galleries with and without ASCs, it was evident that the former were less integrated. Considering HH in all galleries ($3.1 \leq HH \leq 17.5$) the lowest values occurred in those with ASCs regardless of the family ($3.1 \leq HH \leq 3.9$), while in galleries without ASCs values lower than 7.8 were not registered.

Based on these findings, the galleries without ASCs performed much better in terms of visual integration, indicating that the more progressive a gallery, the more visitors can explore it. Since the highest HH values were in the main gallery, there would be greater chances for visitors to be seen and to see other people in such space, reinforcing its relevance as a social space.

VC measures the number of direct connections from a space considering the visual connections to inform how much one space is visually connected to another. Considering all layouts VC behaved less linearly than HH, with most recurrent values reasonably balanced, as follows: 26% ($606 \leq VC \leq 699$); 22% ($408 \leq VC \leq 496$) and 20.5% ($501 \leq VC \leq 591$). Out of these, 65% were galleries with ASCs.

Similar to HH values, the highest VC values occurred in galleries without ASCs, including (5) cases within the 800-1000 and 700-799 ranges, and (13) cases varying from 600 to 699. Although not by a very large margin, based on these results, we could say that more progressive galleries are likely to present higher VC values.

Regarding visual intelligibility (R2), 78% of all galleries were considered intelligible (R2 ≥ 0.50), amongst which, 26 out of 27 were galleries with ASCs. Within the niched family, higher R2 values were almost evenly spread in galleries with shallow, medium and deep cavities (2, 1 and 1 cases respectively). Overall, the majority of medium to high R2 values in layouts without ASCs occurred in galleries with double wall deformation (10 cases), with only 3 cases of unilateral deformation (Table 1).

As 78% of all variations were visually intelligible and higher HH values occurred in the main gallery, it is plausible to confirm the research hypothesis that progressive galleries have highly intelligible visual fields or that progression is closely related to both higher HH values and connectivity degree.

	SINUSOID				CHAMFER				NICHE			
	Gallery Layout	Visual Integration (HH)	Visual Connectivity (VC)	Visual Intelligibility (R2)	Gallery Layout	Visual Integration (HH)	Visual Connectivity (VC)	Visual Intelligibility (R2)	Gallery Layout	Visual Integration (HH)	Visual Connectivity (VC)	Visual Intelligibility (R2)
Without Aggregate Spatial Cells (ASCs)		515.01	654.93	0.115		451.23	699.57	0.127		217.36	660.11	0.292
		168.09	735.92	0.316		281.9	751.72	0.096		88.86	673.88	0.718
		160.78	731.45	0.35		299.91	749.16	0.091		87.11	673.58	0.715
		157	670.82	0.249		277.18	718.74	0.094		58.47	644.78	0.71
		69.56	778.34	0.636		97.47	800.88	0.369		31.07	665.43	0.932
		64.59	764.18	0.638		89.11	795.8	0.482		30.56	663.94	0.928
		68.67	689.25	0.538		128.08	734.56	0.085		39.43	633.83	0.837
		36.68	817.79	0.8		47.71	860.12	0.719		22.89	661.95	0.963
		37.12	809.97	0.813		45.58	849.72	0.712		22.45	667.67	0.961
With ASCs		14.52	505.36	0.924		14.75	501.59	0.928		13.45	467.49	0.939
		15.88	580.6	0.923		16.44	591.16	0.923		13.61	507.09	0.944
		16.95	583.81	0.924		17.54	606.48	0.917		13.66	507.53	0.944
		8.09	426.8	0.912		7.84	398.56	0.92		6.84	348.97	0.903
		8.31	485.06	0.912		8.66	496.38	0.924		7.59	429.6	0.917
		8.26	478.34	0.918		8.33	491.93	0.91		7.38	408.04	0.918
		7.96	419.97	0.917		7.89	425.51	0.898		7.13	373.03	0.895
		8.31	566.75	0.917		9	567.91	0.904		7.58	439.06	0.906
		9	548.51	0.924		8.95	562.81	0.907		7.5	435.6	0.909

○ No correlation (R2 ≤ 0) ○ Insignificant (0 < R2 ≤ 2.0) - 11% ● Light (0.21 ≤ R2 ≤ 0.39) - 9.5% ● Moderate (0.40 ≤ R2 ≤ 0.69) - 7.5%
● Pronounced (0.70 ≤ R2 ≤ 0.89) - 16.5% ● Very Pronounced (0.90 ≤ R2 ≤ 0.99) - 55.5% ● Perfect (R2 = 1.0)

Table 1: Visual intelligibility values (R2) for all 54 PG variations.

4.1.3 Agent-based analysis

Starting by examining gate counts the distribution of flows were isolated in (4) groups according to the number of agents in descending order: group 1 (8-12 and 8-11); group 2 (7-10 and 7-11); group 3 (6-8 to 6-9 and 5-7 to 5-9), and group 4 (4-5 and 4-6). Looking at all galleries, the densest flows (7-12 agents) were slightly more recurrent in the galleries without ASCs (52%) than in those with ASCs (48%).

The highest count cases (8-11; 8-12) occurred in three shallow galleries, two double sinusoids (symmetric and asymmetric) and a single niche gallery, but amongst the two densest groups there were (13) cases with ASCs and (16) cases without. Thus, the busiest gates were more common in galleries without ASCs. Reinforcing this condition two of the cases with less busy gates (4-5 and 4-6) were observed in galleries with ASCs, and only one case without.

We also observed that denser gates were more recurring along the central axis of the main galleries, justifying the general pattern of destination selection and confirming the strength of this space. Only one single chamfer gallery with ASCs in multiple rings showed a dense gate outside the main gallery.

In order to compare agent behaviour and HH patterns, we overlapped the densest flows from gate maps with the locations of HH peaks, which showed that, in general, these did not coincide, leading to some specific observations.

First, the coinciding peak locations were more recurring in double-niche galleries with medium depth cavities and in one case with deeper niches. Three of these galleries did not have ASCs and one did. Some overlapping occurred in (3) cases of sinusoid double galleries with deep cavities and (1) with medium cavities, but not as clearly shown as in the niche galleries. In chamfer galleries no overlapping was detected. Amongst the (7) cases with noticeable overlapping, (4) had ASCs and (3) did not. Regarding such examples, one had single wall-deformation and the others had both walls deformed, equally split between symmetric and asymmetric conditions. None of these cases presented shallow cavities (Figure 5).

Therefore, we did not find confluence between higher gate density and HH values. When it did occur, the shape of the limiting barriers appeared to be influential, as a significant overlapping was evident in some niche layouts. However, HH peaks were much lower in these galleries, with values decaying as cavities became deeper. In such cases more visual fields were needed to see the entire gallery, even more when they gained ASCs. Nevertheless, the most privileged visual fields in niche galleries, in general, were larger than in the other families, especially in the layouts with the highest gate flows.

Trail maps were another important part of the agent-based analyses. The densest nesting of trails occurred near the central axis of the main gallery. There were also a considerable number of paths in cavities, especially in the deeper ones, but not much flow was found in the ASCs. We computed the number of routes that passed through such cavities according to its wall deformation, shape and depth, with first 20 agents (AG) navigating simultaneously in each.

Considering all layouts, more agents were active in cavities in the galleries without ASCs (AG=477) than in the ones with ASCs (AG=448), perhaps because, in the latter, permeabilities between cavities led agents to explore the cells, reducing activity in the cavities. The most frequently visited cavity was C03 (at the entry's opposite end), followed by C06 (right of the entry, at lower wall) in the double galleries without ASCs. Considering all layouts, there was greater activity in galleries with deep cavities and less flow in galleries with shallow cavities. The presence of more agents in deeper cavities coincided with higher degrees of VC and higher values of visual R2 in layouts. HH and VC analyses pointed to slightly higher values in the chamfer galleries, possibly because these required less informational effort than the jagged geometry of the niche galleries.

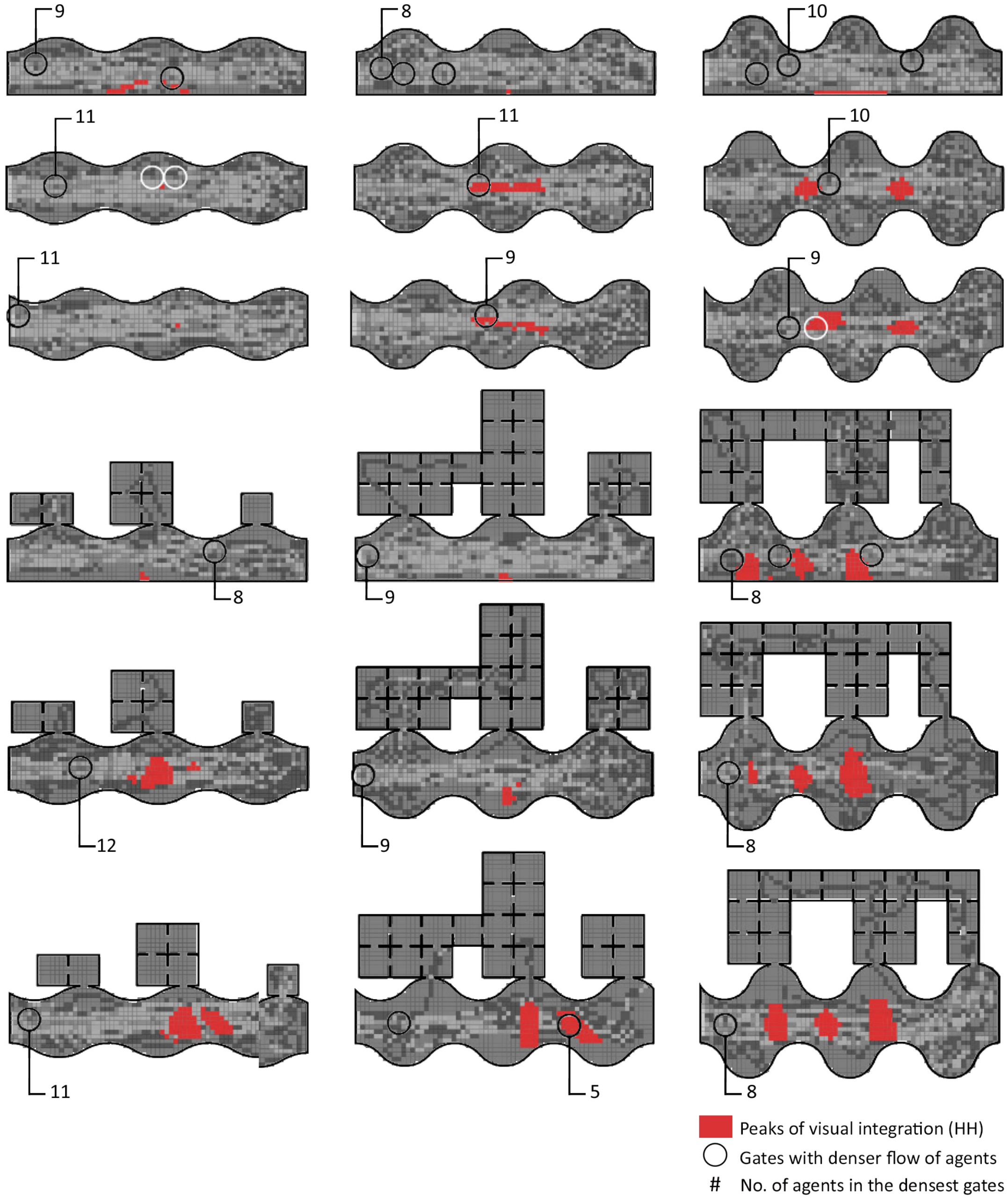

Figure 5: Peaks of visual integration (HH) overlapped with the densest flows from gate count maps of sinusoid galleries.

To match VR experiments trail maps of 10 agents were observed in medium sinusoid galleries layouts, showing greater agent movement in cavities C01 and C03, both registering (17) routes. Comparing the double symmetrical and asymmetrical layouts**,** more paths were found in cavity C03 of the asymmetric layout. In both simulations (20 and 10 agents), there was a greater flow of paths in cavity C03, but with 10 agents, more paths were registered in the double asymmetric gallery.

Regarding the PG matrix initially stated, gate counts and trail maps confirmed the concentration of occupation and movement along the central axis of the main gallery, regardless of shape or cavity depth. In addition, the densest trail clusters were more often seen in the main gallery than in cavities or added cells, reinforcing the progression in such spaces.

4.2 Experiments in Immersive Virtual Reality

The VR and EEG-based analyses involved paths / spatial behaviour and metric of focus. After extracting data from digital platforms, and subsequently organizing it in two groups of galleries - with art (GwA) and without art (GwoA) - we produced mappings of routes and, from these, maps of peaks of focus (PF) per visitors' responses, which indicated the location of the highest values. The remaining steps, in short, consisted of clippings and overlapping of such mappings that aimed to establish relationships between spatial behaviour and brain responses.

We first mapped all PFs for each visitor regardless of the value (0-100), then restricted these to higher rates (51 -100). Afterwards, the Index of Variation of Peaks of Focus (IVPF) was computed to express the alternation between PFs, casting light on the fact that a high level of task switching and oscillation of peaks may indicate lack of focus and distraction.

4.2.1 Visitors' paths

All visits followed the same sequence of galleries, first the single (S), then the double symmetric (DS) and lastly the double asymmetric (DA) layout. Trails and visitation times were registered to verify their relationship with visitation sequence and gallery type. We also counted visitors' paths in the cavities.

The overall visitation time per gallery was 93 seconds (s). In general, the visitor who spent the most time in one gallery did the same in the others. All subjects spent slightly more time in the first gallery and very similar periods of time in the other two, perhaps due to the initial interest effect, which is often reduced as the action of exploring additional galleries repeats (Melton 1935, p.262).

Longer visits occurred in GwA (S type) and the shortest in the DA without art (28s). All shorter visits (up to 50s) took place in GwoA. This significant time difference can probably be explained by the greater amount of elements to explore in GwA.

Observing route patterns and visitation times showed that, regardless of gallery shape and whether or not they exhibited art, routes were more concentrated in the main gallery than in cavities, matching the agents' behaviour. Overall, a higher percentage of agents entered cavities than visitors, and their paths were also more sprawled (Figure 6).

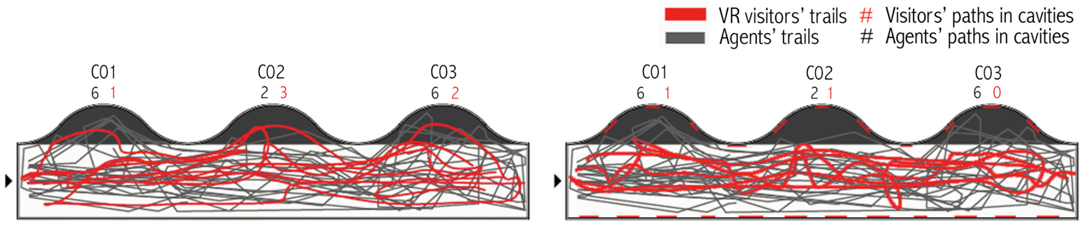

Figure 6: trail maps of 10 agents and 10 visitors in a single sinusoid gallery without (left) and with (right) art, indicating number of paths in cavities.

Overall, between agents and visitors, the routes in GwoA resulted in a slightly more dispersed pattern than the denser nesting in GwA. Quantity-wise, there were (29) routes in the former's cavities and only (17) in the latter's.

4.2.2 Visitors' focus

The EmotivBCI application provided the essential information for the Peaks of Focus (PFs) graph. Overall, the data representation we developed was experimental and aimed to facilitate visual associations with the syntactic analyses. Based on Melton (1935, p.47), PF values observed the following scale of significance: none (zero); insignificant (1-10); very light (11-30); mild (31-50); moderate (51-70); pronounced (71-90) and very pronounced (91-100). PFs were shown in layouts referencing their point of origin and direction of viewing (dot with arrow).

The highest PF averages (PFa) registered in all gallery families, without and with art (GwoA; GwA) were, as follows: S (PFa=41;PFa=39), DS (PFa=37.5; PFa=31) and DA (PFa=31.8; PFa=22.6). As a whole, PFs were lower than moderate, remaining in the mild range (31-50), except for the DA gallery without art (22.6). Therefore, we could say that the response of focus did not have a good overall performance.

A low correlation (R2) between duration of visits and PF values was observed. Cases of very long visits scored very low average of values and, conversely, high values were obtained during shorter visits. In general, including Gwa and GwoA, single galleries (S) showed the lowest value (R2=0.25), increasing in the DS and DA galleries (respectively, 0.44 and 0.65).

Amongst all PF values computed (1-100 range), quantitatively, the total number of peaks per family, without and with art (GwoA; GwA) was respectively: S (61; 59), DS (53; 61) and DA (both 58). Isolating the highest peaks (51-100 range), although numbers were very similar, there was a slight higher quantity in the S galleries, and, amongst these, a difference between the DS

(35 peaks) and the others (44 peaks each) was noteworthy. Based on these results, it seems that the presence of art did not have a significant influence on how often PFs were reached.

Considering the quantity and values of PF and time spent in all galleries, the results suggest a relevant aspect. Just like the duration of the visits decreased after the first gallery (S), the number of PFs behaved the same way. Clusters of PFs were also mapped, first individually then overlapping all galleries types. Especially in the GwoA, routes were more dispersed, running closer to cavities, which could indicate a more exploratory visit, but, at the same time, due to the lack of an orientation point (Tröndle 2014), with less focus.

In GwA, where lower focus rates occurred, trails were more densely nested and concentrated in the main gallery, but the (more sprawled) spatial patterns of PFs and paths looked more alike in galleries without art, which may indicate that visitors' focus was more affected by the geometry of the gallery.

To further verify such influence, we also mapped visitors' views in all galleries. Wherever the overlapping of views and PFs was greater, there was a clear difference in the visual behaviour in galleries without and with art. In the former, regardless of shape, when they were more focused, visitors' view coincided and pointed towards the end of the gallery.

In GwA, the areas of greater overlapping of views were spread more evenly across the galleries. The suggestion that views were influenced by the presence of art seems plausible, leading to dispersion through the layouts. As in these cases paths were mostly contained in the main gallery, it is possible that while the body movement remained more controlled (due to limited trajectory options), head turns provided views that looked for the works of art. As seen previously, more visits took place in cavities in GwoA, coinciding with the highest occurrence of PFs, which computed (8) peaks more than in GwA. The cavity in GwoA with more PFs coincided with the most visited one (CO2), but there was no agreement regarding cavities in GwA.

More PFs were registered in the DS gallery and the most recurring routes in the DA gallery, which presented the same number of peaks than the S gallery (9 PFs each). These results ratified that visitors explored the layout outside the main gallery more often when there was no art. Regarding focus x cavities, PFs valued scored higher when cavities occurred in GwoA.

Lastly, the IVPF was introduced to assess the extent to which PF values varied. Calculating such index required (3) steps: extracting the curve and grid from the graph of focus for each visitor; computing the number of peaks or slopes in grid intervals and, adding and dividing these values by the total number of intervals.

As an example, for a given subject navigating the S, DS and DA galleries with art, the IVPFs were, respectively: 2.07; 1.57 and 1.25. In this case, there was a greater variation in the S gallery, which may be indicative of less attention. In the DA gallery, the situation was reversed, registering the smallest oscillation. This condition was confirmed by carefully observing the graph curves.

The IVPFs presented the following breakdown for all galleries, without and with art (GwoA; GwA): S (1.93; 1.94), DS (2.07; 2.56) and DA (1.88; 2.67). All indexes were higher in galleries with art. In the S gallery they were practically identical (1.93 and 1.94), but in the remaining spaces they increased more significantly, especially in the DA galleries (from 1.88 to 2.67). Calculating the correlation (R2) between the IVPF indexes in the three galleries and the time spent in these by each subject, in general, there was a very high R2, with 60% of the cases showing an almost perfect correlation (0.93 - 0.99), 20% a pronounced R2 (0.76-0.79) and only two atypical cases of very low R2 values (0.13 and 0.22).

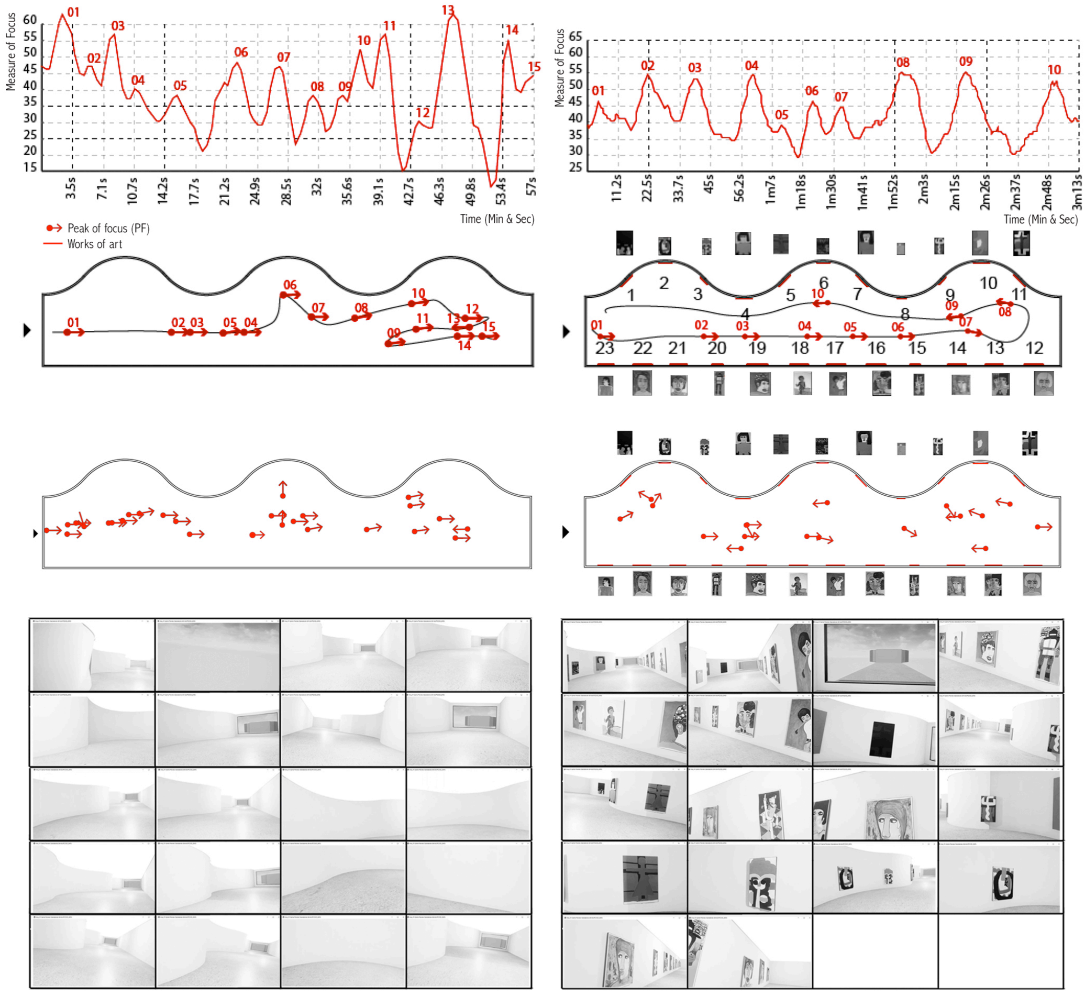

Figure7: PF graphs, mappings and views (at peaks) of two subjects; one navigating a gallery without art (left) and the other, a gallery with art (right)

As we have seen, the highest averages of focus were registered in GwoA, and, according to IVPF values, in these galleries there was less variation of PFs, indicating consistency in the data. Conversely, such results showed that in GwA, probably due to the informational effort required by artwork, the values of focus oscillated more frequently, leading to relatively more distracted behaviour than in GwoA (Figure 7).

4.3 VR experiments x syntactic analyses

Here we will concentrate on contrasting VR visitors' trails and focus responses with visibility and agent-based evaluations regarding HH, VC and the agent flow in gates.

Visitor trails x agent flow in gates

By overlapping the maps of the densest visitor trails with the busiest gates, we confirmed that routes were concentrated in the main gallery. However, this also showed that the most visited areas did not always coincide with denser gate locations, and that the presence of art did not seem to affect such relationship.

Peaks of focus values x dense agent flows

Higher PF values and denser flows were more coincident in the S gallery. There was a significant difference between the PF locations in GwoA and GwA. In the former, PFs coincided with denser agent flows, and in the latter, the peaks were more dispersed. The overlap of PFs with gate counts (GC), respectively in GwoA and GwA, resulted as following: S – 26 PFs (11 GCs), 17 PFs (4 GCs); DS - 27 PFs (6 GCs), 17 PFs (2 GCs); DA – 22PFs (4 GCs), and 13 PFs without overlap. This showed that regardless of the geometry, there were more overlaps of PFs with denser gates in GwoA, which also registered the highest overall averages of focus. Thus, in GwoA, PFs occurred more often in places with a greater flow of agents and, conversely, in GwA, PFs seemed to be affected by the art. In GwA, where art pieces could be seen from the main gallery, it is possible that while the visitor's gaze wandered towards several works simultaneously, their focus decreased.

Visual integration (HH) x Peaks of focus

If positions with greater HH imply where the other spaces can be seen from a single view, PFs did not necessarily occur where visitors had a broader view of the space. The highest PF value (91) was shown in the DA gallery without art and was oriented towards the exterior opening. Aimed towards a sequence of artworks, the lowest PF (55) occurred in the S gallery with art. We also overlapped the highest PF values and views from such peaks with the areas of greater HH. More coincidences occurred in the DS GwoA, where 41% of PFs overlapped with the most integrated locations. In the DS GwA, this percentage was reduced by almost half (23.5%). In the single GwoA and GwA, no PF locations coincided with those with higher HH values. Percentages were lower in DA than in the DS galleries (Figure 8).

In all cases, the overlap between PFs and higher HH nodes decreased in GwoA, which is consistent with visitors' trails and agent flow in gates. By overlapping visitors' views in GwA and GwoA simultaneously, a stronger relationship with HH occurred in the DS gallery, and, in general, at least one of the areas most glimpsed by visitors coincided with higher HH locations.

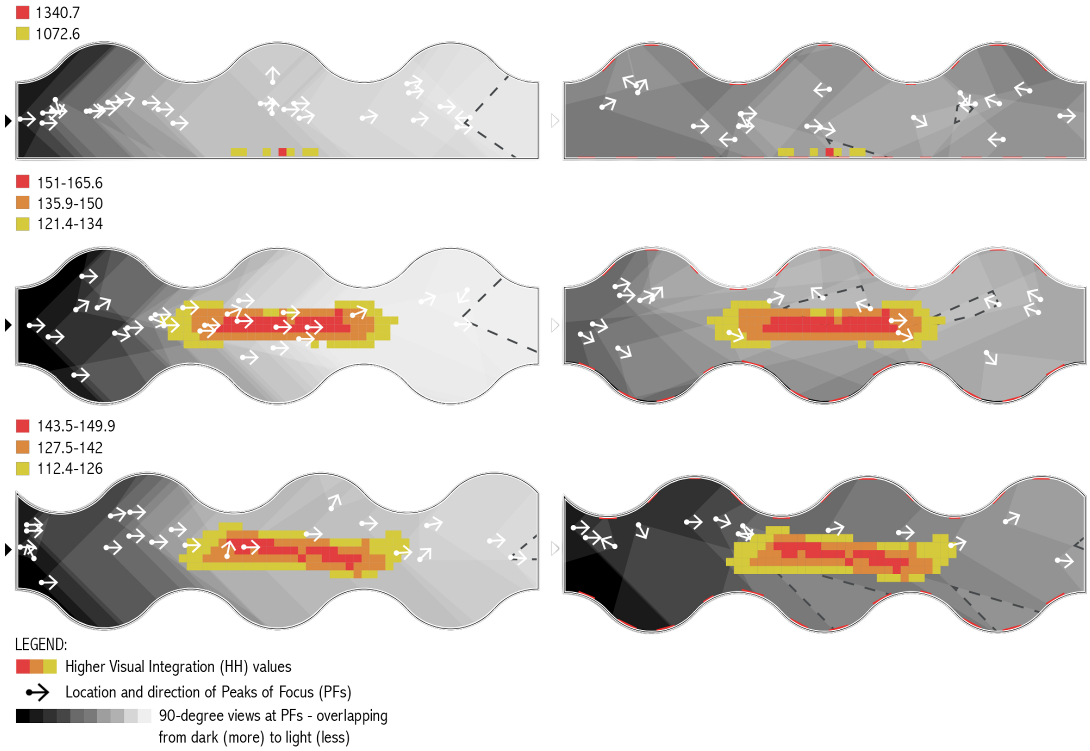

Figure 8: mappings of PFs (51-100 range) of all visitors overlapped with 90-degree views from PFs and higher visual integration (HH) areas in all galleries without art (left) and with art (right).

Focus x VC x HH

We correlated focus, VC and HH measures for each GwA and GwoA. This involved PF values from each visitor and the HH and VC values at the location of these peaks. As for VC, respectively, in GwoA and GwA, the correlations were, as follows: non-existent (73%, 53%); insignificant ($R2 \leq 0.20$) - 13.5%, 33%; mild ($0.21 \leq R2 \leq 0.39$) - 13.5%, 7%) and one moderate case ($0.40 \leq R2 \leq 0.69$) in the DA gallery. Regarding the correlation with the VC degree, the following occurred: non-existent (67%, 46.5%); insignificant -26%, 33.5%; mild (7%, 6.5%), with two moderate cases of DA with and without art.

In general, the lack of correlation between PF and HH values was predominant, with only (3) cases of moderate R2, which matched the more recurring overlaps of views with PFs. Similarly, regarding visual connection correlation was non-existent in 67% of all cases.

The visual fields from which visitors could to see the entire space (located in the main gallery) seemed to be greatly affected by the type of wall deformation in galleries. If fields like these (with more intervisibility) tend to ease navigation and increase sociability, the widening of visual fields in our experiments did not seem sine qua non for visitors to reach good focus.

5 CONCLUSIONS

Throughout these analyses we aimed to unravel the PG morphology based on hypothetical layouts, which derived from the spatial characteristics of historical PGs, the GM and the MUG. Based on the SS approach, specially through agent-based analyses, and on the neuroscientific notion of the cognitive function of focus, we tried to find clues to better understand how key aspects of the PG - direct relationship between sequential spaces and layout exploration, intelligible navigation and to strong social space and co-presence - affected spatial behaviour.

While the SS approach cast light on these issues, after extracting and analysing data from experiments in immersive VR with PG layouts, the neuroscience-based evaluation showed that the coexistence of these characteristics did not necessarily lead to good response of focus, which was weakened in layouts with works of art and/or by the well-known fatigue effect in museums, which may cause a continuous decrease in the visitors interest.

Based on results, we created seesaw diagrams to visually synthesize the associations observed between syntactic measures and the degree of progression (DoP) in PGs. The following relationships were then established: lower RC values indicated a higher DoP; a lower MD represented a higher DoP; lower HH matched higher DoPs; a higher VC degree related to lower DoPs, and lastly, stronger intelligibility (R2) indicated a to higher DoP (Figure 9).

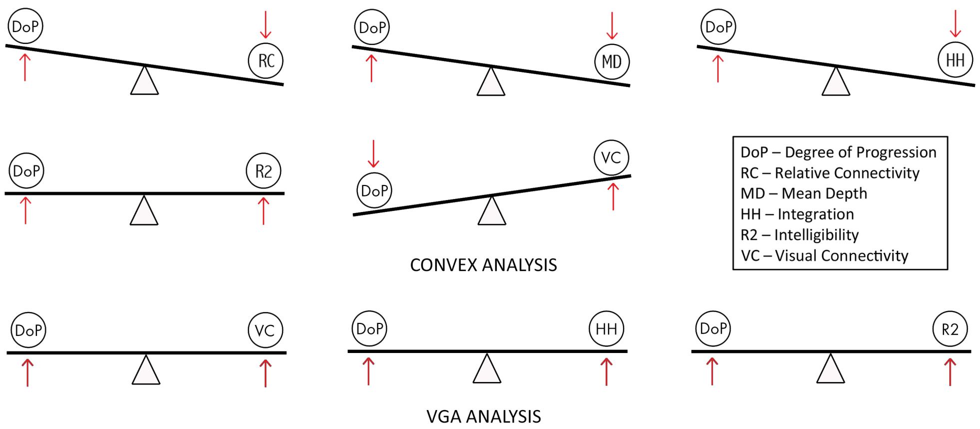

Figure 9: Seesaw diagrams showing the relationship between the Degree of Progression (DoP) and the syntactic properties through convex and VGA analyses of PG layouts.

Average R2 values from convex analyses showed a pronounced correlation in all layouts (R2=0.72). Higher R2 values occurred in galleries without ASCs, confirming our initial hypothesis that the more progressive, the more intelligible layouts are. Visual intelligibility wise, higher R2 values were found in double galleries without ASCs. Confirming the hypothesis that PGs' predominant visual fields were highly intelligible, 78% of all variations showed high R2 values. Overall, a higher DoP related to greater values of HH and VC.

In conclusion, we could not assure that all PGs per se would lead to low focus responses. To further examine the issue, additional experiments would have to be conducted, perhaps introducing more wall deformation types in the main gallery and specific post-navigation tasks. However, based on our sampling, the coexistence of intelligibility, more intervisibile fields and a route-defining geometry did not always lead to a visitation experience to which visitors respond with greater focus. This is where the progressive gallery paradox is revealed.

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