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Perceptual evaluation of plausibility of virtual furniture layouts

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Abstract

As realistic virtual environments become more important, it is interesting to examine procedural generation. In this work, plausibility of virtual furniture layouts was evaluated in a perceptual study comparing layouts by a professional human interior designer with layout variants rearranged by a C# algorithm. It attached related furniture sides at specified distances in groups. Rasterized furniture footprints were tested, and layouts without overlaps between furniture or their clearance areas were accepted. The algorithm was inspired by Germer and Schwarz (2009), and the evaluation methodology by Yu et al. (2011). The algorithm was run by a Unity tool which placed furniture models in a virtual 3D room. Human-made layouts were also visualized and all layouts presented for 2 and 10 seconds with participants tasked to assess if they were human-made or not.

The algorithm fulfilling side-based spatial relation constraints and clearance area constraints did not prove to produce as plausible virtual layouts as those by a human designer, but these constraints significantly improved the perceptual plausibility versus semi-arbitrary furniture placement with only wall-placement constraints for relevant furniture. Perceived orderliness of both human-made and generated layouts was significantly positively correlated with plausibility. The evaluation also provided knowledge of what characteristics are perceived as tells of procedural generation rather than human interior design.

Sammanfattning

Då realistiska virtuella miljöer blir viktigare är det intressant att undersöka processuell generering. I detta arbete utvärderades trovärdigheten av virtuella möbellayouter i en perceptuell studie som jämförde layouter gjorda av en inredningsdesigner med layoutvariationer omarrangerade av en C#-algoritm. Den satte ihop relaterade möbelsidor på specificerade avstånd i grupper. Rasteriserade möbelavtryck testades och layouter utan överlapp mellan möbler eller deras friytor accepterades. Algoritmen var inspirerad av Germer och Schwarz (2009) och utvärderingen av Yu et al. (2011). Ett Unity-verktyg placerade möbler i ett virtuellt 3D-rum. Designer-layouter visualiserades också och alla layouter visades i 2 & 10 sekunder för deltagare som bedömde om de var arrangerade av människa eller ej.

Algoritmen som uppfyllde spatiala sidorelationsvillkor och villkor för fria ytor visade sig inte producera lika trovärdiga virtuella layouter som de gjorda av en människa, men dessa villkor förbättrade trovärdigheten signifikant jämfört med semi-godtycklig möbelplacering med enbart väggplaceringsvillkor för relevanta möbler. Uppfattad nivå av ordning var för både de mänskliga och genererade layouterna signifikant positivt korrelerad med deras trovärdighet. Utvärderingen gav också kunskap om vad som uppfattas som tecken för datorgenerering snarare än mänsklig inredning.

Author keywords

procedural generation; furniture arrangement; perception

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1 Introduction

Visualizations of building interiors are used in many fields such as computer games, architectural visualizations, and simulations. Detailed virtual buildings are becoming more important with the emergence of VR (virtual reality) technologies, expansive game worlds, and increased digitalization in the architectural field. If the windows of virtual building exteriors are rendered translucently, their interiors can be visible from the outside, and therefore empty rooms may need to be furnished. Choosing furniture and placing them in every virtual room manually can be an arduous and time-consuming task. An algorithm for automatically generating sensible furniture layouts for each type of residential room would cut down on such work. Procedural generation can take long time to run, and the result might lack human touch and include illogical placements since not all aspects are considered by an algorithm. Such cues of synthetic generation can be seen in procedurally generated layouts in figure 1.

Figure 1. Layout generated by this project's algorithm (left) and layout generated by Yu et al.'s (2011) *algorithm (right). Note for example chairs not placed in the conventional arrangement around the dining table and the floor lamp positioned far away from any seating area such as the armchair which is inconveniently placed beside the TV set.*

The challenges of developing and programming an algorithm for procedural generation of furniture layouts stem from the complexity of the problem. Interior design is a human activity with multiple possible goals and preferences. There is no clear solution to what pieces of furniture are chosen or how they are placed in a room. Due to the high complexity, not much work has been done on individual aspects of procedural furniture layout generation. Most papers have included various assumptions and abstractions of the interior design process and only evaluated one factor – 'realism' – of furniture layouts generated by their own specific algorithm.

The project included programming a base-line algorithm (see *section 3.3*) for procedural furniture layout generation employing side-based spatial relation constraints between functionally dependant furniture and respecting specified furniture clearance areas. Spatial relation constraints were implemented following the principle of specified sides of certain furniture being placed at a specified distance from other furniture's sides of a specified compatible side type, such as a sofa front side at a specified distance from a TV front side. A custom tool used the algorithm to place furniture models in virtual rooms, which were used as stimuli in a perceptual evaluation of the layouts.

When looking at buildings from outside, interiors are only visible through windows and that limits visibility. For this reason, furniture layouts in the evaluation were rendered using the *Unity 3D* engine in first-person perspective looking through windows into the room from the outside.

1.1 Objective and purpose

In this project, plausibility was evaluated by tasking participants to assess if virtual layouts were generated by a computer or made by a human, as that can be a better measure than asking for a rating of realism, which can be a nebulous term. Points of interest were finding the immediate cues of procedural generation, adjusting generated layouts to remove those cues to verify if they affect plausibility, and testing whether short exposure when looking in at a furniture layout from outside improves plausibility versus longer exposure. Layouts were evaluated in terms of plausibility, orderliness, and whether the rooms were lived-in or vacated.

Aside from the other auxiliary purposes mentioned above, the main purpose of the project was to evaluate the plausibility of the generated and human-made furniture layouts in order to identify characteristics of furniture layouts that cue a viewer into perceiving them as synthetically generated.

As virtual worlds become bigger and more complex, the use for automatic world generation grows. Procedural world generation is layered and can go from the macro scale to the micro scale; each layer emulates a different part and requires a different generation procedure. One can generate the landscape to set generated cities in, which in their turn house generated structures and buildings, which in turn have generated interior rooms, which are furnished with furniture that are placed using a procedural method. Even more granular features, and other virtual world content needed for an application, could be generated procedurally with appropriate procedural techniques.

Figure 2. Architectural visualizations by Swedish construction companies (left) NCC (2017), (middle) Veidekke (2015), and (right) Peab (2012).

Many architectural visualizations still employ reflective and completely non-transparent rendering of windows without visible interior contents, see examples in figure 2. Furnished building models are tedious to produce (Brauer et al., 2008) and procedural content generation can help reduce the costs of creating content

(De Carli et al., 2011). If the view is only from the outside looking in, generated interiors may only need to look plausible though visually-obstructing façades with windows. This can be applicable to pre-rendered still images, videos, and games or simulations where the camera movement is restricted to outdoors.

1.2 Research question

"How plausible are human-constructed and procedurally generated furniture layouts perceived as in virtual space when passing by windows looking in, and what layout aspects affect plausibility?"

As virtual environments are becoming more important, furnished interiors, even if just seen from outside virtual buildings through windows, can play a role in making a plausible virtual environment. Sufficiently plausible automatic procedural placement of furniture may remove the need for arduous manual placement. Therefore, it was interesting to investigate answers to this research question. While the procedural generation method in this work is computerized, resulting furniture layouts could be used in real life.

In future society, advanced algorithmic techniques may augment human professional work to automatically create blueprints for real-life interior design optimized for space-usage, functionality, and ergonomics. Using extensive user data, interior designs could possibly be customized to match the specific tastes and needs of the occupants. For work spaces, organizational needs and workflows could be taken into account. In virtual environments, furniture layout generation algorithms can be attractive in generation of game worlds, serious simulations, and set-pieces for video production (Smelik et al., 2014), for example.

The research methodology was initiated with a review of previous work on procedural furniture layout generation to inform the design of the algorithm developed in this work. Papers on evaluation of and perception of architectural spaces and virtual environments were studied to absorb available knowledge. A perceptual study was chosen as a suitable methodology for researching how people perceive virtual furniture layouts. As the most immediate application of procedural furniture layout generation is for layouts in virtual environments, perception of virtual interior scenes is relevant to investigate. Still, not all virtual environments are experienced in the same way. For this experiment, virtual layouts were simply presented on a 2D screen with constrained camera movement and interactivity.

1.2.1 Sub-objectives

In order to broaden the implications of the research question, the project was decomposed into the following sub-objectives:

- To evaluate perceptual orderliness of the virtual scenes (SO_1)
- To evaluate whether adjustments to hide synthetic generation cues improve plausibility (SO_2)
- To compare plausibility of furniture layouts generated by algorithm enforcing side-based spatial relation constraints to layouts generated according to naive arbitrary random placement (SO_3)

Orderliness is defined as the state of being orderly i.e. tidy or arranged in some order or pattern (Merriam-Webster, 2018a, 2018b). In Westphal-Fitch's (2012) investigation of the human 'sense of order', it was found that humans when creating patterns have a propensity to group them hierarchically and make them symmetrical around axes. The perceptual orderliness of furniture layouts was evaluated to see how orderly or unorderly the different classes of manual and synthetic layouts would be perceived in virtual space, and to see if there was any correlation between perceived plausibility and orderliness.

To determine if specific deficiencies can successfully be removed to improve layout plausibility, adjusted furniture layouts were evaluated as a separate class of layouts. While there are no scientific papers recommending arbitrary placement as a method for arranging furniture in virtual rooms, that would be the most baseline algorithm for procedural furniture layout generation. Procedural generation often heavily relies on randomization but it is often used in order to achieve variation. The main algorithm for procedural furniture placement in this work uses randomization for that purpose. By comparing layouts generated by this main algorithm (see *section 3.3*) to semi-arbitrarily generated layouts (see *section 3.5*), difference in perceptual plausibility that the additional rules bring could become apparent.

1.2.2 Hypotheses

It was expected that procedurally generated layouts following side-based spatial relation constraints – i.e. furniture placed in relation to relevant furniture sides – would not be perceived as just as plausible as human-constructed furniture layouts. However, it was also presumed (for SO_3) that the side-based spatial relation constraints would significantly improve the procedural generation of furniture layouts versus a naive random furniture placement algorithm without such considerations implemented.

It was also presumed that plausibility would be negatively impacted by features incongruent with people's cognitive models of how interior objects are conventionally arranged. Structured adjustments to remove author-identified synthetic cues were expected (for SO_2) to improve the plausibility of adjusted layouts. Perceived orderliness of the presented furniture layouts was further hypothesized to be correlated with perceived plausibility (for SO_1), since humans like to surround themselves with visual patterns that follow some kind of structural order (Westphal-Fitch et al., 2012).

Generated layout plausibility was not expected to rival the plausibility of human-constructed layouts since the professional interior designer explained that personal aesthetic considerations, knowledge of conventional and complex functional relations between furniture placements, and tacit knowledge were applied – none of which the algorithm emulated. However, it was of interest to see how much such a simple algorithm could improve on a naive arbitrary placement of furniture in a room.

1.3 Delimitations

Furniture layouts in this work refer to the floor surface position and orientation of a set of interior objects in a room – not their visual appearance nor their height above the floor. The developed algorithm was less sophisticated than the optimization-based algorithms studied as background. The focus was instead on how people can distinguish automatically generated furniture layouts from manually made furniture layouts. The algorithm developed in C# processed furniture dimensions and their spatial relation semantics from an XML file. Related furniture was attached to each other at those specified distances in groups. The specified rectangular furniture footprints were used to test for overlaps in a rasterized grid of the virtual room. The rooms were all residential living rooms, their floor plans only rectangular, and furniture was restricted to axis-aligned orientations. Any layouts where there were no overlaps between furniture, or between furniture and any clearance areas specified around furniture, were accepted. The author specifically investigated the perception of the plausibility of furniture layouts when seen through the partially obscured perspective of looking in through windows.

In the evaluation only three questions were posed to the participants for each furniture layout (see *section 4.1.6*). More bipolar rating scales for other opposite descriptive terms could have been included for investigating additional perceptual dimensions. Adjectives from the environmental psychology field, such as the 36 adjectives described in de Laval's (2004) paper on architecture dialogue with laypeople, were not included in the evaluation due to the concern that participants would focus too much on the visual presentation of the layouts rather than furniture placements. Further, so many additional questions would probably cause fatigue and make the experiment take too much time.

1.4 Structure

This paper goes over previous algorithms for furniture arrangement and theories useful for constructing the evaluation and interpreting its results in *chapter 2*. How the furniture layouts used as stimuli were made and specifically how the main algorithm for furniture placement was implemented is expounded upon in *chapter 3*. How process of how these stimuli were evaluated to find out how the layouts would be perceived is explained in *chapter 4*. Results from the questionnaires and from oral responses are presented in *chapter 5*. Interpretations of the results are then discussed in *chapter 6* and the conclusions in *chapter 7*.

2 Previous work

As described in the previous chapter, larger virtual worlds entail the use of procedural generation algorithms. Different procedures for generating furniture placement from previous work are discussed herein. In order to evaluate the perception of virtual layouts, human visual perception and related study designs were explored in *section 2.3*.

2.1 Placement algorithms

There have been many papers on procedural generation of a room's furniture layout. The heart of the problem lies in answering two questions – what furniture or objects should be placed, and where they should be positioned and oriented. Ideal interior design should be functional and aesthetically pleasing. Aesthetics are highly subjective and difficult to formalize, but basic functionality is the most important aspect for functional rooms. The selection of furniture could also be augmented by parametrically generating custom furniture or altering furniture in some way. Furniture selection or furniture generation was not part of this project, only perception of their placements. Example layouts generated by studied algorithms can be seen in figure 3.

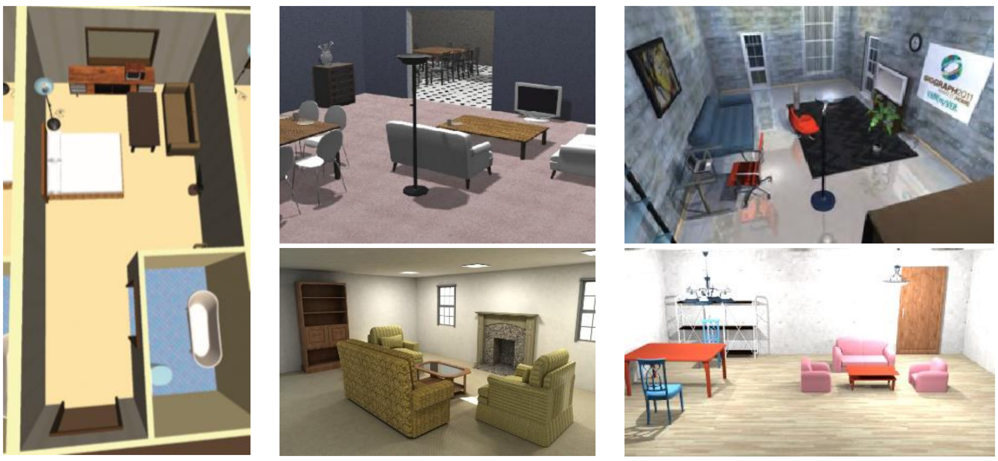

Figure 3. Furniture layouts generated by: A. (left) a deterministic algorithm (Germer & Schwarz, 2009), *B. (top-centre) another deterministic algorithm* (Tutenel et al., 2009), *C. (top-right) an optimization-based algorithm* (Yu et al., 2011), *D. (bottom-centre) another optimization-based algorithm developed using interior design guidelines* (Merrell et al., 2011), *& E. (bottom-right) a similar optimization-based algorithm also taking lighting levels into account* (Yamakawa et al., 2016).

2.1.1 Optimization-based algorithms

One method of solving the problem is through an optimization algorithm, where a good layout is numerically expressed in an objective function that generated layouts are measured against. Layouts are formed by step-wise changes to a layout that can be rolled-back if the custom objective function returns a worse result. Merrell et al. (2011) developed such a method where furniture moved and placements were evaluated through an algorithm that was developed to quantize how well furniture placement fulfilled common interior design guidelines. The novelty of Merrell et al.'s method was that it incorporated aesthetic evaluation in the algorithm. In the algorithm's objective function, both functional and aesthetic criteria were numerically calculated and weighted. The aesthetic criteria included *balance* of furniture footprint areas around the room's centroid, rectilinear *alignment* of furniture relative to each other and to the wall, and *emphasis* as balance of furniture around centroids of furniture groups. The functional criteria quantized overlaps of defined furniture *clearance areas*, *circulation* by checking the number of connectable person-wide discs, and *pairwise relationship* fulfilment by comparing paired furniture distances to defined ideal distances. Yu et al. (2011) also developed an optimization-based algorithm with different methods for quantizing layout success, such as checking overlap of rectangular segments along smooth Bezier curves between doors. Yamakawa et al. (2016) developed an optimization algorithm that also took lighting into account. It used radiosity calculations of window light, and had a term for conformance to optimal illuminance for various furniture in the algorithm's objective function. These algorithms were computationally heavy, and unfeasible for real-time use. Less sophisticated algorithms that forgo using optimization techniques and use more deterministic or rule-based placement of furniture can be faster.

2.1.2 Deterministic algorithms

Germer and Schwarz (2009) developed a less complex furniture arrangement system in order to achieve runtime speeds suitable for real-time use. Using a deterministic randomisation function, a fast system could save storage space by producing exact furniture layouts from just stored seed numbers as keys. All furniture items were sorted in a dependency hierarchy and were placed in the room in order from the highest *parent* level to the most dependant level. *Children* attached themselves to one of the up to six unobstructed supported faces of the parent bounding box and thus became part of the parent's group unit. These units then moved independently to possibly "rejig" the arrangement if the first arrangement did not fit all furniture to be placed. If an overlap occurred, the unit was broken up and the children would search for a parent again. This approach was not optimal for arrangements in dense rooms because it simply tried random locations until everything fitted in. If children had semantic information to be placed to the parent's side and not on top, they were placed at a random position alongside the edge facing the parent.

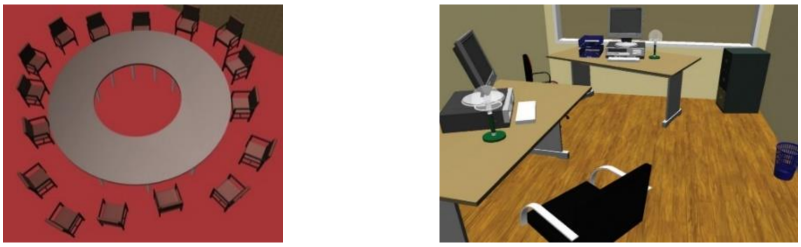

Figure 4. Chairs squarely around circular table (left) and untidy office interiors (right) (Germer & Schwarz, 2009).

Fundamentally the system only checked for furniture overlaps – no other interior design criteria – and only supported basic contact constraints around boxes. High level semantics such as ergonomics, room usage, or aesthetics were not implemented. Also, using rectangular bounding boxes caused issues with non-rectangular parents, for example chairs not being arranged circularly around round tables (see fig. 4). Tutenel et al. (2009) created a similar system that also considered clearance areas around each piece of furniture. Many deterministic algorithms (Tutenel et al., 2009; Xu et al., 2002) used Minkowski sum to test for overlaps between furniture.

2.1.3 Clutter

Yu et al. (Yu et al., 2016) presented a tool for assisting user selection of natural clutter. A database of kitchen photographs was analysed, and all small clutter items attached to surface areas were catalogued. From this semantic information, the system could suggest clutter for every kind of surface in a kitchen, with probability proportional to real world statistics. This was made to produce natural, lived-in interior scenes. Since this project focused on evaluating procedural placements of pre-selected furniture, furniture such as bookcases were empty and the layout clutter-free. Yu et al. called synthetic interior scenes "without the odds and ends that populate real-word scenes" eerily barren and devoid of life. In this project, that presumably affected the evaluated perception of this project's generated layout scenes.

2.1.4 Types of layouts

Algorithms can be more or less flexible and offer different levels of tool user control. Some tools (Xu et al., 2002; Yu et al., 2016) were developed which allowed users to select surfaces and be presented with a list of placeable objects that were semantically defined to be supported by that type of surface. Some methods implemented 'types of interiors' expressed as various parameters used by their algorithm to produce a specific type of furniture layout. Germer and Schwartz (2009) implemented a *tidiness* parameter that affected random rotational and positional offset to furniture placement (see fig. 4) and could be used for creating untidy "abandoned houses". They also suggested using a *room type* parameter – e.g. office, kitchen, or lounge – for selecting the furniture to be placed, and a *style* parameter for using different sets of furniture models consistent with that style's culture or time period. Xu et al.'s (2002) tool used a deterministic algorithm with a set of weights proportional to the selection probability for every "child object's supported parent faces" for connecting related interior objects. The user could select between different *scenarios*, such as "after supper" where the weighting for the plate's supported parent surface "sink top" would increase appropriately. These systems rely on vast and accurate semantic databases for the best results.

2.2 Furniture relation data

While interior designers can place furniture at their own accord, there are functional dimensions defined in various guidelines. Similarly, many observations of furniture placement relations – such as the placement of a TV in front of a coffee table and facing a TV – can be translated into rules and procedures that use semantics from a pre-defined semantic class library (Tutenel et al., 2009). When defining the relational distances between pairs of furniture for this project, values were taken from English (Johnson, 2010) and Swedish guidelines (Bygglovalliansen, 2010) and manuals (Bodin, Hidemark, & Stintzing, 2008). The furniture measurements used in this project were defined to be proportional to their 3D models, and were similar to the furniture measurements mentioned in the guidelines and manuals. Doors and window dimensions followed common Swedish dimensions (Bodin et al., 2008) with 0.90 m wide clearance areas to allow passage by windows and to allow for opening doors. Sensible clearance areas were defined for object sides that needed space in front of them to be functional. For example, the armchair front side clearance area stretched 0.30 m to fit a person's feet, and the front-side of a cabinet had a 1.00 m long clearance area to allow a person to open the drawers. The TV's front side clearance area stretched 1.8 m in front of it to allow for unobstructed viewing at the optimum viewing distance as defined by THX (THX Ltd., 2009). To build vast databases of semantics accurate to real-world scenes, it would be beneficial to follow a formalized method of collecting data. Yu et al.'s (2016) method of analysing what types of surfaces clutter laid on in real photographs, was by employing manual workers through the online crowd-labour service *Amazon Mechanical Turk*. Fisher et al. (2012) developed a machine learning method of analysing 3D example scenes to automatically infer spatial object relations from their occurrence in each other's neighbourhoods. After processing many example scenes, the system could build probabilistic offset map variants depending on occurrence of other objects using Bayesian networks.

2.3 Perceptual study design

The most sophisticated algorithms would benefit from a strong evaluation methodology that accurately captures the perception of the resulting layouts. While developing algorithms, empirical evidence of the perceptions of layouts would also be more useful than expert evaluation when deciding if certain features are cues of synthetic generation or not. Simpler methods that target real-time generation could also use results from perceptual studies of layouts as the basis for improving their computing speed and not needlessly adding complexity.

2.3.1 Visual perception

Visual perception enables us to form conceptions of the existence, shape, and position of external objects (von Helmholtz & Southall, 2005), but we only pay attention to a small amount of a visual scene (Duncan & Humphreys, 1989). From studying the fixations and saccades of human gaze, researchers have inferred the existence of two viewing time–dependant cognitive modes of visual processing (Follet et al., 2011; Krishna et al., 2017). While the nature of those modes remains a matter of investigation, one commonly used separation is into ambient mode and focal mode concerning processing of spatial content and of object detail respectively (Krishna et al., 2017). Velichkovsky et al. (2005) suggested that initial processing of an image's spatial information may finish when fixation times and saccade amplitudes stabilize, which happened after around 2 seconds and 3–4 seconds respectively in their study of object recognition in interior scenes.

2.3.2 Cognition theories

There are many theories of how human perception and reasoning works, but psychological research has provided glimpses into the partitioning of mental structures (DiMaggio, 1997). A *schema* is a term for a structured pattern of thoughts for organizing information into categories and organizing relationships between ideas. *Schemas* are formed when individuals make sense of information through prior experiences and are used as a framework for categorizing and understanding new information in the future (Carlson, 2017). Each schema is a network of learned related features, that when perceived, propositions the mind to classify such new information into a corresponding category (Stillings et al., 1995). Schemas are changed or formed to accommodate new information. Learning requires understanding general principles. (Gould, 2012). 'Scene schemas' contain semantic knowledge of what objects are likely to be found in a type of scene and how they would be spatially positioned in relation to each other. In addition they contain generic world scene knowledge such as the fact that a stapler should not float in the air (Henderson, 2003). Psychological research points to two modes of general cognition – automatic and deliberate. While automatic cognition is fast, unverbalized, and automatic, it relies on available schemas. Deliberate cognition is slow, verbalized (mentally), and deliberate. People often use deliberate processing when they are asked to attend to a problem or when their schemas cannot accommodate new information (DiMaggio, 1997).

2.3.3 Looking-in perspective

In virtual environments, third-person and first-person perspectives are generally available to users (Salamin et al., 2010). First-person perspective is used to provide an egocentric perspective to immerse the user in the environment (Chittaro & Scagnetto, 2001). Floor plans with furniture are drawn in a top-down perspective and are ideal for showing furniture placements (Rengel, 2012). Furniture placements might be less apparent from a first-person perspective. Virtual buildings have many occluding surfaces (Chittaro & Scagnetto, 2001), and architects sometimes use cut-away ceilings and walls in illustrations to remove occlusion. This allows users to understand the overall structure of architectural environments. Interfaces with mere camera zoom and rotation around fully modelled buildings do not allow that, because floors and walls conceal most of the interiors. First-person walkthrough interfaces that allow users to move inside the rooms help the user to understand the interiors (Niederauer et al., 2003). It can be inferred that first-person perspectives from the outside, looking in, might be less helpful because of occluding walls and floors. Ennis et al. (2011) investigated the plausibility of crowd formations from different perspectives, and found that randomized character positions and orientations were perceived as more realistic from first-person eye-level viewpoints than from canonical, isometric, or top-down viewpoints.

Many cognitive researchers and theorists have emphasized how cognition is shaped by bodily experiences and actions (Geeraerts, 2006; Landriscina, 2013). For example, our concept of *balance* is learnt from early bodily experiences and this ‘balance schema’ is used to understand visual balance metaphorically and analogically as equal weights around a central axis (Geeraerts, 2006). Physical objects convey information about how people can use them. The ways in which a person can interact with an object are called *affordances*, and they depend on the person’s mind and bodily capabilities (Norman, 2013).

2.3.4 Think-aloud methodology

Think-aloud protocols are a widely used method for user testing of software, interfaces, and documents. The principle of think-aloud protocols is for participants to verbalize aloud everything going through their mind while performing tasks relating to the matter to-be-tested. The method is part of a well-respected research paradigm focusing on human cognition during the execution of tasks, such as choosing between options (Van Den Haak et al., 2003). The think-aloud technique relies on the fact that people relatively accurately can report thoughts in their short-term memory, and is done in order to gather information about the underlying mental processes. The responses are transcribed and analysed afterwards by an investigator who usually categorizes and quantifies the thoughts expressed in some form of content analysis (Lang, 2014).

2.3.5 Related study designs

Evaluation methodology used for eliciting discussions and opinions about architecture from uninitiated laypeople have been developed in the *environmental psychology* field. Different methods can be useful for finding practical problems with the environment, learning what people find salient, and what feelings the environment induces. One such method, *semantic environment description*, uses a questionnaire of many bipolar Likert scales between opposing adjectives to initiate discussions (de Laval, 2004). Environmental psychology examines the built and natural environment’s influence on humans (Steg et al., 2012), while the focus of this work was to investigate the plausibility of *virtual* interior environments. Ucelli et al. (1999) performed a perceptual study of how well people comprehended computer rendered images (of variable fidelity) of a real building’s interior and exterior. They compared results of semantic environment description questionnaires filled in by people inside the real building and people viewing the outline-only renderings, basic shading renderings, renderings with simple textures, and renderings photo-retouched with people, suitable items, and backgrounds. They found that people evaluated the images of all types very closely to the real architectural environment. Kort et al. (2003) compared perceptions of virtual and real environments for environmental psychology use. After a walkthrough of a real or replicated virtual room, participants who saw the real room sketched significantly more accurate cognitive maps of it compared to participants who saw the virtual room.

Germer and Schwarz (2009) merely used researcher observation of their procedurally generated furniture layouts to identify deficiencies, and classed them as “very realistic”, “acceptable and still realistic with minor deficiencies”, or “not convincing with deficiencies that would not appear in real rooms”. They commented on the need for formalized user studies to more precisely measure the quality of procedurally generated layouts compared to human-modelled interiors. Merrell et al. (2011) instead employed two professional interior designers to decide which they preferred of each pair of algorithm-assisted furniture arrangements or purely manually made furniture arrangements in identical rooms. Yu et al. (2011) similarly showed their synthetic and manual furniture arrangements pair-wise, and prompted participants to pick the one they preferred. Unlike the Merrell et al. (2011) study, Yu et al. (2011) forced a choice for each pair and also used participants with no interior design expertise. Each of Yu et al.’s 25 participants were shown 70 pairs.

2.4 Relevance to work

In *section 2.3*, previous evaluations of virtual interior scenes as well as general theories of visual perception and cognition were studied for improving the design of the perceptual study (see *chapter 4*) and for interpreting the results (see *chapter 6*). Accurate data is required for accurate results and functional furniture dimensions were researched as described in *section 2.2*. The algorithm in this work was informed by the design of the previous furniture placement algorithms described in *section 2.1*. The next chapter describes how it was developed.

3 Implementation

The placement algorithm developed in this project largely followed the template of previous deterministic algorithms described in *section 2.1.2*. In this algorithm, furniture was placed without overlaps at set distances from specified related furniture sides, and with specified surrounding clearance areas being kept unoccupied. A Unity tool for synthesizing furniture layouts used as stimuli in the perceptual study (see *chapter 4*) was developed to arrange furniture 3D models according to furniture positions and orientations given by the programmed algorithm. Aside from the algorithm-generated layouts, there were other classes of layouts used as stimuli in the perceptual study for comparison. In total, there were four types of furniture layouts: manually constructed by a human interior designer (L_M), generated by the side-based constraint algorithm (L_G), highly randomized layouts (L_R), and the generated layouts mirrored and adjusted (L_A) to follow rules for hiding cues of the procedural generation. These layouts are hereafter denoted L_M, L_G, L_R, and L_A, respectively.

3.1 Room basis

As the human interior designer was tasked to create many living room layouts using a limited set of interior objects and capabilities, it was decided that there should be different variants of empty rooms the designer was tasked to decorate.

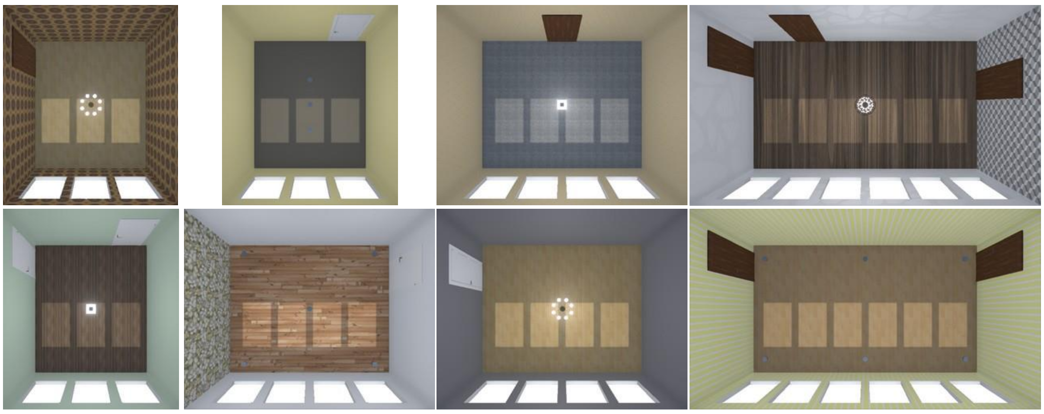

Figure 5. The eight empty rooms used as a basis for furniture layouts in the experiment, viewed from a top-down perspective.

One of the differences was *room size*. The eight rectangular rooms used were of three different sizes. There were three 3.5 m × 4 m rooms, three 5 m × 4 m rooms, and two 7 m × 4 m rooms – equating areas 14 m^2, 20 m^2, and 28 m^2. These room sizes will be referred to herein as small, medium, and large. A ninth room of large size was omitted (see *section 4.2*) from the analysis. The walls surrounding the floor were 0.2 m thick and 2.6 m high which is a common ceiling height and higher than Swedish standard minimum (Bygglovalliansen, 2010). The rooms had one wall with three, four, or six windows respectively – equating roughly the same number of windows per square metre floor, to let in the same amount of sunlight. Each window was 0.9 m wide and 1.5 m tall with 0.2 m between each. The 3D models of the empty rooms were made in open-source interior design program *Sweet Home 3D* (Puybaret, 2018), and exported to Unity.

The eight rooms (see fig. 5) had different exterior and interior textures, as well as varying numbers of doors, different door positions, and different ceiling lights. This gave the human interior designer different “canvases” to populate with interior objects.

3.2 Manual layouts (L_M)

The furniture layouts L_M made by an actual interior designer with professional experience served as the basis for what interior objects were rearranged in the L_G, L_A, and L_R layouts. The human interior designer was allowed to change the interior wall texture and floor texture to other options. The placement of interior objects for all the eight rooms was done in Unity. The designer could view the design from any angle in both parallel projection and orthographic projection, but could only place objects in the floor plane; the height component was fixed. Objects were not allowed to overlap in the top-down view, even if they would not actually intersect e.g. a wall painting over a sofa. This was a restriction so the algorithm would be able to find a solution – as it only solved placements in the floor plane. Continuous rotations in the plane were possible, but the designer almost exclusively used 90° orientations congruent with the cardinal directions of the rooms. The designer picked from 43 different interior object models to place in the room from a list, which can be seen in figure 6.

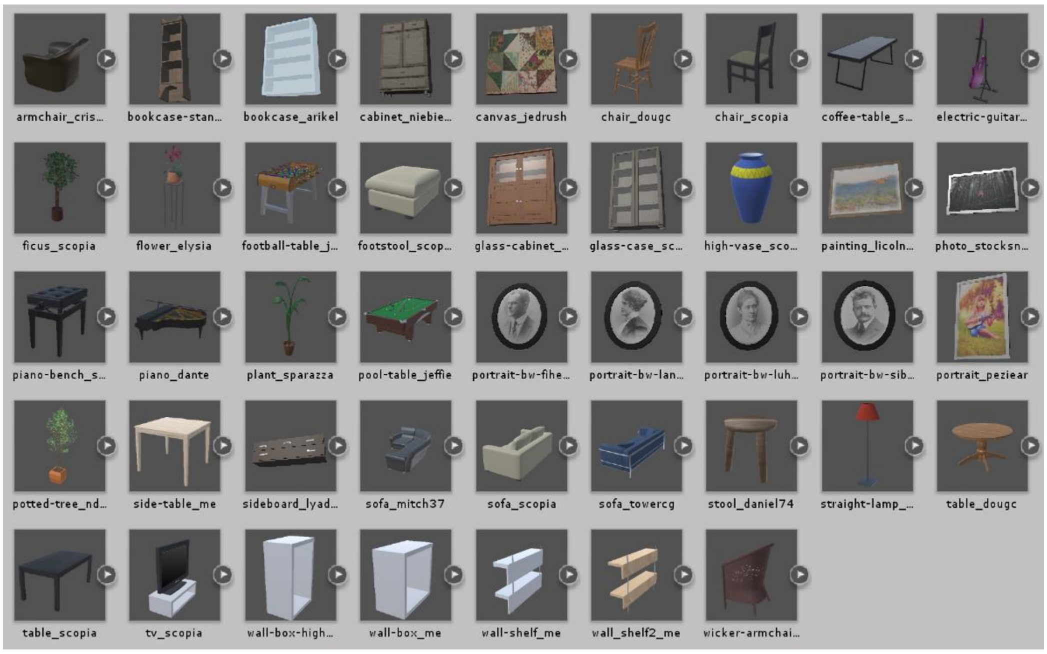

Figure 6. Catalogue of interior object 3D models available to the designer.

There were no carpets available to the designer since in the algorithm, that would count as a solid object taking up the full height of normal furniture, possibly rendering layout completion impossible.

3.3 Layout generation algorithm (L_G)

The tool for generating the L_G evaluation stimuli used the C# 6.0–programmed algorithm with side-based spatial relation constraints (see fig.7 for an overview) inspired by the deterministic furniture layout generation algorithms described in *section 2.1.2*. It took one of the manually furnished L_M rooms and rearranged the same furniture within the same room, according to the rules set out. It read a flat database XML file for retrieving the furniture model semantics, such as dimensions, surrounding clearance area dimensions, references to the visual representation objects of the models, what types of sides (faces) each furniture object has, and if they should be placed in relation to other specific types of furniture sides and then how far offset.

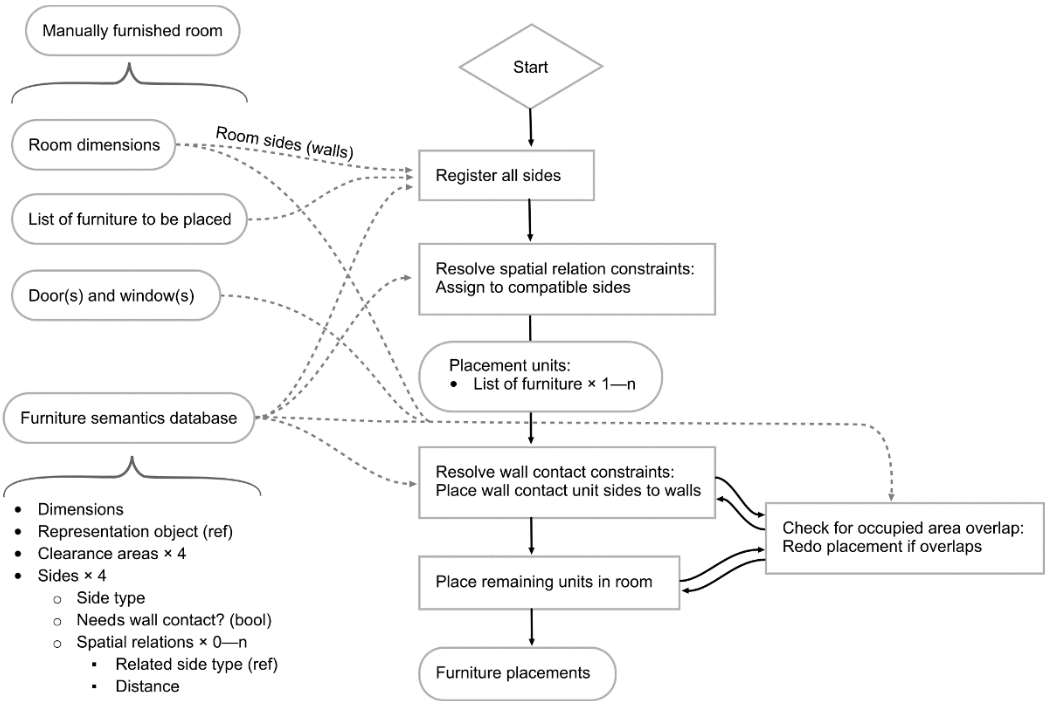

Figure 7. Graph showing how semantics data is processed by the algorithm to produce a layout L_G. Input data (left) and procedure (right) are shown.

The fact that much of interior design involves organizing objects into functional groups and that such arrangements tend to be simple and straightforward (Rengel, 2012) was exploited using side-based spatial relation constraints. From the set of to-be-placed furniture (identical to the L_M), all their sides (four per object) were saved in a list in memory. Each spatial relation constraint for sides was resolved by first finding sides of compatible side type from that list. The distribution of two objects assigned to the same side was even along the side, but when there were many compatible sides, objects were assigned to the least occupied side. The attacher object was set at the distance specified by the constraint, with the attacher side facing the compatible support side. Related furniture was in that way placed in placement units. Objects without spatial relations to other objects were put in stand-alone placement units. See the procedure in pseudocode for fulfilling side-based spatial relation constraints in figure 8.

```
• Load interior object semantics (such as dimensions, sides, side-relation-constraints)

• Set rectangular room data (width, depth, height, door data, window data)
• Get list of interior objects to be placed
• Assign each object into a unique placement unit (any attached objects will join this
  unit so transforms will affect them together without affecting their configuration)

• Register all furniture sides (interior objects x4)

• Assign attacher sides to supporter sides (of other interior objects and walls)

• For each support side:
   • Rotate attacher side (and its objects) to face support side

   • Move attacher side (and its objects) to match specified support side distance

   • Merge placement units by reassigning the attacher side object to the support side
     object's placement unit

• For each remaining (consolidated) placement unit:
   • Register maximum one or two wall attacher sides (from the wall attacher sides of
     unit member objects) as placement unit wall constraints

   • Set placement domain (all positions in room grid fitting between walls, or next to
     walls if wall constraints set)

   • Shuffle placement domain

• Recursively test placements (from placement domains) for all placement units until no
  overlap occurs

• If placements are found without overlaps between interior objects (or their clearance
  areas) of all placement units:
   • Return finished list of interior object placements
• Else:
   • Return empty placement list
```

Figure 8. Simplified pseudocode for the furniture placement algorithm.

The geometric solver algorithm was programmed using rasterized overlap checking. The room was rasterized into 0.05 m × 0.05 m squares with information of any window or door clearance areas. Each placement unit had its own domain of all possible placements spaced 0.05 m apart fitting between the walls of the room. Some placement units had sides that were specified to be up against the wall, and their domains only included placements next to a room wall. Each domain's placements were then shuffled using deterministic (if a seed key was given) or time-based randomization, and iterated through recursively. Placements were accepted if their footprint did not overlap with raster squares occupied by furniture placed earlier, their clearance areas, or window/door clearance areas. Placement of furniture shorter than the window sill were accepted on the clearance areas of windows. After an accepted placement was found for all placement units, the resulting L_G furniture layout consisted of positions and orientations for each piece of furniture in the set. The tool then placed the furniture representation 3D models in the virtual 3D room using Unity.

3.4 Adjusted layouts (L_A)

The L_G furniture layouts were inspected both from above and from the first-person perspective, and cues that looked completely implausible logically or aesthetically as well as cues that looked possibly unnatural were identified by the author. The layouts were adjusted to remove these cues as detailed in table 1. Furthermore, the diagonals between the clearance areas was also enforced by moving out overlapping furniture. When these adjusted layouts L_A were presented to the study participants they were mirrored in order to avoid identification with the base layout.

C_n	*	Synthetic cue	Adjustment
C_1	×	TV in front of door	Move TV placement unit as minimally as possible away from door; if necessary rotate as well
C_2	×	Floor lamp in front of seating	Move floor lamp away from obstructing position
C_3	×	Plant not clearly visible from windows	Move plant to be visible from the windows
C_4	×	Paintings of the same series hung at separated wall positions	Such paintings should be placed at a set short distance from each other
C_5	×	Coffee table not at a reaching distance from sofa seating	Position coffee table at a short distance right in front of sofa seating
C_6	×	Painting in the corner of a room	Move painting at least 10–20 cm away from corner depending on available space
C_7	×	TV not aligned centrally in front of longest sofa seating	Align TV centrally in front of longest sofa seating
C_8	×	Sofa seating pointing towards wall	Rotate sofa placement unit 180°
C_9	¤	Having an unconventional placement of chairs around a table	Place chairs according to the conventional chair–table configuration
C_{10}	¤	Table not placed against wall	Slide table side up against wall if possible
C_{11}	¤	Two plants right next to each other	Move one plant away from the other
C_{12}	¤	Floor lamp not close to wall	Position floor lamp close to wall
C_{13}	¤	Paintings right next to other furniture/doors/windows	Move paintings away at least 5 cm or centrally in free wall space
C_{14}	¤	TV near wall behind but still a fair distance away from it	Push TV back towards the wall
C_{15}	¤	Shelves behind doors	Move shelves minimally away from back of door

Table 1. Author-observed cues of synthetic layouts and adjustments made to hide them.
** × = Completely implausible feature ¤ = Possible unnatural feature*

These cues emerged because of inadequacies of the layout generation algorithm. Further possible cues may also be considered, but the following cues were ignored due to lack of justification or difficulty to remove by specific adjustments:

- Blocked-off areas

- Sofa in front of windows
- Unused space
- Sofas/armchairs in close proximity but still not part of the same sofa group
- Lack of walk paths

3.5 Randomized layouts (L_R)

The eight specific semi-arbitrary layouts L_R used were made by re-arranging the objects from the corresponding manual layouts in the corresponding room using a simple algorithm. It ensured all interior objects from the manual layout were placed in the rectangular floor plane without overlap. Objects with sides defined to be facing wall were placed at the specified distance, but at a random position along the walls. All other objects were randomly placed at arbitrary positions. If any overlap was detected the object was placed anew. Clearance areas around the objects were not considered. The eight resulting L_R layouts from the randomization algorithm were used for all participants in the perceptual test. Their visualizations were mirrored so half of all the rooms presented would be mirrored, as the adjusted layouts L_A were already mirrored (see *section 3.4.1*).

3.6 3D visualizations

Visualizations (see fig. 9) were created based on the different furniture layouts (see fig. 10) and these resulting animations were used as the layout stimuli in the evaluation. Creative Commons–licenced models of the interior objects were downloaded from a stock 3D model library (Scopia Visual Interfaces Systems, 2017) and a user-submitted 3D model site (Blend Swap, 2017). Other public domain textures and images were downloaded from Open Game Art (2017), Pixabay (2017), Public Domain Pictures (2017), and Wikimedia Commons (2017). Some 3D models and images were made by, or modified by the author.

The texture material settings were set to match the appropriate physical properties using normal maps, smoothness values, and metallicity values. The visualizations were pre-rendered in Unity 2017, using gamma colour space, a subtle screen-space ambient occlusion to show depth and the shape of furniture realistically, screen-space reflections to show surface reflectiveness, bloom lighting for realistic lamp rendering, and individual light sources from ceiling lights. To emulate daylight, a directional light with a light-yellow tint shone down at a 45° angle through the windows together with subdued blue ambient lighting. All lights cast smooth shadows. As for rendering the window glass, no reflection was rendered since reflections are highly variable depending on the lighting situation. Visibility could be lower if reflections were rendered realistically. However, the glass was rendered using a 90% transparent black quad to emulate a typical visible light transmittance of clear glass (Tuchinda, Srivannaboon, & Lim, 2006). The super-sampled renderings were downscaled to 1280×720 pixels and combined to high bit-rate MPEG1-encoded video files.

Figure 9. Visualizations of room #5 (selectively mirrored) with identical object sets in four different layouts. In clockwise order from top-left corner: manual (L_M), randomized (L_R), generated-adjusted (L_A), and generated layouts (L_G).

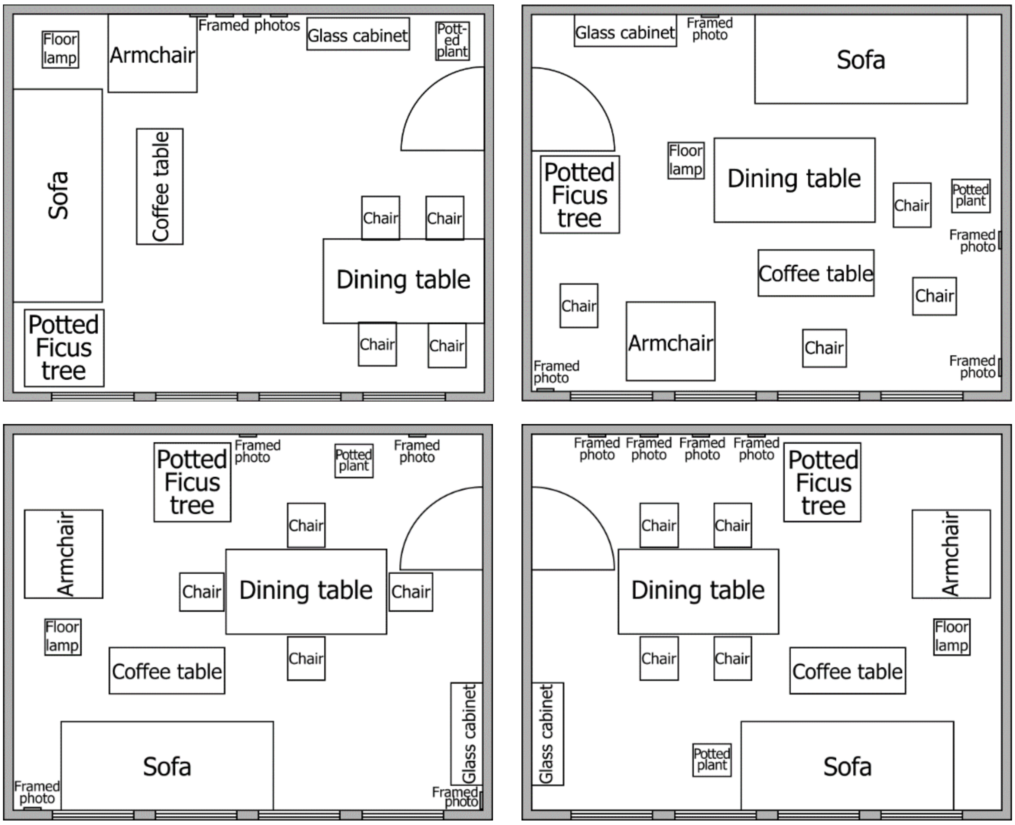

Figure 10. Floor plans of room #5 (selectively mirrored) with the aforementioned four layouts. In clockwise order from top-left corner: manual (L_M), randomized (L_R), generated-adjusted (L_A), and generated layouts (L_G).

3.7 Use in evaluation

The main generated layouts L_G (see *section 3.3*) were prepared and measured against layouts prepared by a human interior designer L_M (see *section 3.2*) as a point of comparison. In generated-adjusted layouts L_A (see *section 3.4*), author-identified synthetic cues were removed in order to evaluate their effect on plausibility. As a basic point of comparison, a rudimentary randomized placement algorithm was used to produce layouts L_R without any side-based spatial relation constraints or clearance area constraints (see *section 3.5*). The next chapter describes how the four classes of layouts were presented when evaluating their plausibility.

4 Perceptual study

This project used a custom algorithm for generating the furniture layouts as described in *chapter 3*. The layouts were visualized in Unity 3D and presented on a computer monitor as the perceptual study's stimuli. Evaluation involved participants viewing both synthetically and manually furnished interiors, and asking them to rate each furniture layout in relevant perceptual dimensions. Additionally, think-aloud methodology (see *section 2.3.4* for explanation) was chosen in order to get a better of understanding of how participants would perceive the layouts and to allow them to freely express any issues they might perceive.

4.1 Experiment details

4.1.1 Stimuli and conditions

In this perceptual study, eight rooms were furnished in the four layout fashions L_M (*manual*), L_G (*generated*), L_A (*generated-adjusted*), and L_R (*randomized*) as described in *chapter 3*, so that 32 different layouts were shown and analysed. Figures 9 and 10 show the four layout variants of one room. These four classes of layouts were the different conditions exposed to the study participants as stimuli.

4.1.2 Participants

The 20 participants of mixed sexes were recruited from the university campus. Following ethical principles, participants were informed in advance about the general purpose of the study, what they would be doing, and that published results would not be personally identifiable. It was explained that they were permitted to withdraw participation without stating reason at any time, and that questions could be asked at any time. They then signed a consent form, and filled in basic personal information. All participants completed all experiment tasks. Participation was completely voluntary and was compensated with a box of chocolates.

The age of the participants ranged between 20–37 years old; mean age was 25.3 years old. 18 of 20 participants had experience of navigation in 3D environments such as 3D videogames, and the experiment only required simple mouse-controlled navigation in one axis. All participants had normal or corrected-to-normal vision. 11 out of 20 participants had done personal interior design, but no one had professional experience. Think-aloud sessions were conducted in either Swedish (fifteen participants) or English (five participants) according to participant preference.

4.1.3 Experiment procedure

The experiment was carried out over 20 individual sessions; one for each participant. First, the experiment participants were briefly exposed to the furniture layouts, as seen by an outdoor pedestrian walking past a room, looking in through its windows. The virtual camera used 60° field-of-view, and swept from left to right (see fig. 11) along a 0.82-m stretch alongside the mid-segment of the window wall, 1.5 m back from it, and 1.55 m above floor level. The 1280×720-pixel room sweep videos were shown in 1:1 scale in the middle of a 1920×1080-pixels screen with a black background. In this first section of the experiment, the rooms were shown for 2 seconds each, at 30 frames per second.

Figure 11. The virtual camera position swept from the left side of the room to the right.

After each showing, the participants were asked to assess if the furniture layout was constructed by a human, if the room was lived-in or if it was a non-inhabited show-house layout, and how they rated the orderliness on a 6-point symmetric bipolar scale. After all 36 layouts were shown once, the same set was repeated once in a different order.

After all layouts were shown twice, they were displayed once again, this time in interactable form for 10 seconds each. The test participants had more time to inspect each room layout in the later section and were able to slide back-and-forth freely along the same 0.82-m segment outside of the window wall using a computer mouse. This was technically achieved by participants controlling the video seek and thereby the virtual camera position using the mouse. After each viewing, they were prompted to evaluate and rate the furniture layout by answering the same questions as in first section of the test. However, additional qualitative feedback was gathered as participants were requested to think aloud so their reasoning could be recorded in a notebook.

4.1.4 Tasks

In summary, tasks completed by each participant were as follows:

- Sign consent form
- Fill in basic personal data
- View layout stimuli for 2 seconds and answer questionnaire × 36 times
- Repeat once
- Rewatch layout stimuli for 10 seconds while controlling viewpoint along one axis and answer questionnaire while explaining the reasoning aloud × 36 times

4.1.5 Technical details

Since each participant was to react to layouts 108 times and that would amount to a large amount of data needing to be recorded in a short period of time, it was decided that the testing program should save the results to a spreadsheet document automatically. Therefore, a mouse-controlled application to simplify the perceptual study was created using *Clickteam Fusion 2.5*. The application showed instructions, layouts, as well as questionnaires on screen. It was run on a 15.6-inch monitor with 1920×1080 pixels resolution, positioned at a distance of around 0.60 m from participants’ eyes (suggested by fixed chair distance; no chin-rest or equivalent was used). The layout renderings were shown in a specified order. The application loaded the participant's layout presentation order from prepared spreadsheet files. After each layout, a three-question questionnaire was shown on screen. When participants submitted their answers, there was a 2-second countdown so they would have time to mentally prepare for viewing the layout for 2 seconds, or in the last section, for 10 seconds. After each participant was finished, all results were saved to another spreadsheet document.

4.1.6 Questionnaire

The same questionnaire was presented on screen after each layout shown (see fig. 12). One hindrance to capturing natural reactions when seeing furniture layouts could be if the participants approached the assessment as an analytical task. To mitigate this, participants were primed by the experiment leader and told to think of it as them "walking past a house, looking in through the windows and seeing a living room", and asking them about their *impression* of that layout.

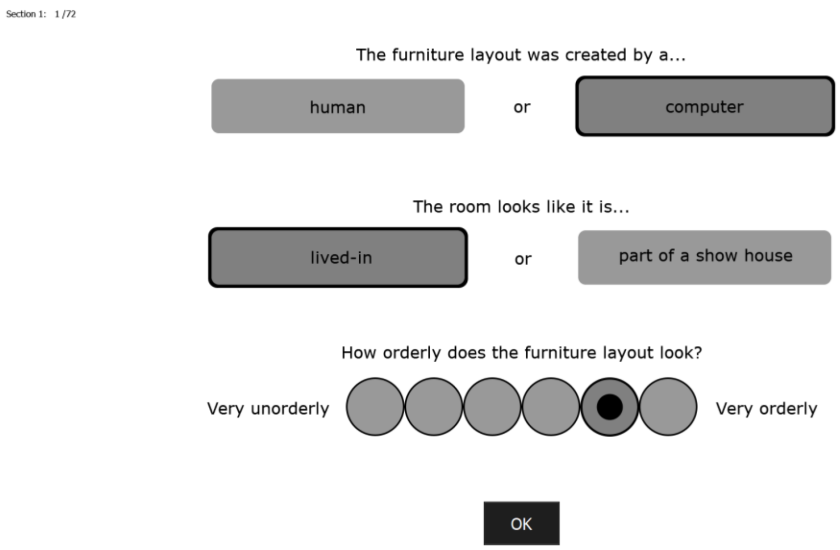

Figure 12. Questionnaire screen displayed after each layout viewing. Colour inverted for paper printing purposes.

The most pertinent feedback was whether the participants would assess the layouts as made by a human or as generated by a computer. The first question of the questionnaire was a forced choice between whether the "furniture layout was created by a…" human or computer. As the question is asking the participants to determine the true binary answer, any continuous scale or discrete scale between the two possible options would simply capture a measure of certainty for either option. A specific point on a continuum may not mean the same thing to different people, even when the end points are labelled (DeVellis, 2016). As furniture can be arranged in different ways depending on the situation, even an unorderly layout could be made by a human to emulate a messy layout caused by, for example, a robbery. It was therefore interesting to see how orderly the layouts were perceived, to get insight into the participants' interpretations. A 6-point symmetric bipolar scale between “Very unorderly” and “Very orderly” was chosen, as 6-point scales have been shown to have a higher reliability and better value discrimination than 5-point scales (Chomeya, 2010). Desire to please the study interviewer may be eliminated by removing the mid-point (Garland, 1991).

As all the rooms were ‘clutter-free’ and all the bookcases empty, it was reasoned that the layouts would not look naturally lived-in, and that might confound the result. Therefore, the participants were asked if they interpreted the rooms as “lived-in” or “part of a show house” – which was explained as being set up for showing the room in preparation for a sale or the room being vacated for sale. This gave the participants an alternative interpretation so they could assess the plausibility of clutter-free furniture layouts.

4.1.7 Order of layouts shown

The same 36 layouts were presented to all participants in three blocks. In the first two blocks, the layouts were shown for 2 seconds each. The same layouts were shown in the same way twice in order to get a measure of how certain the participants were of their assessments. The third block was shown in the second section of the experiment, with each layout available for viewing for 10 seconds. The order of the layouts was counterbalanced using Latin square with regards to the room size and layout class (L_M, L_G, L_A, & L_R). Each participant saw the layouts in a different order.

4.2 Deviations from experiment design

A minor issue was found and corrected after the tenth participant. While the presentation order of the layouts was counterbalanced, it was not sorted for maximal variability from one layout to the next. The same room could repeat immediately with a different furniture layout, which seemed to increase participant boredom. Each layout was separated by several seconds, so there was no possibility for immediate comparison and spotting of differences. Still, the layout order for the final 10 participants was split up into groups to separate identical rooms with different layouts, and counter-balanced within.

After the experiment was conducted, it was discovered that one large room that should have been furnished with the same object set was missing the TV set in the generated L_G, generated-adjusted L_A, and randomized layouts L_R. This was due to human error. The original designer-made layout did have a TV. Thus, the results from those four layouts of the 36 shown were omitted completely, as the objects that were arranged in the layouts differed.

4.3 Data collection

The verbal responses from the think-aloud sessions were written down and transcribed afterwards for effective text content analysis of observed synthetic cues, presented in *section 5.4*. As all results from the questionnaire (see *section 4.1.6*) were saved to a spreadsheet, they could easily be used in statistical analysis. The next chapter presents the results and statistical analysis.

5 Results

All participants completed all the tasks as described in *chapter 4*. As questionnaire answers were stored automatically, means for the different layout classes were established for plausibility, orderliness, and interpretation of inhabitation. Think-aloud interview responses were transcribed and the analysis of them are also presented in this chapter.

5.1 Plausibility

For the 2-second viewings, layouts were assessed to have been human-made 75% SD 18 pp (L_M), 59% SD 23 pp (L_G), 65% SD 19 pp (L_A), & 13% SD 14 pp (L_R) of times for layouts of the human-made, generated, generated-adjusted, and randomized classes respectively. For the 10-second viewings, layouts were assessed to have been human-made 79% SD 20 pp (L_M), 48% SD 28 pp (L_G), 56% SD 28 pp (L_A), & 12% SD 17 pp (L_R) of times for layouts of the human-made, generated, generated-adjusted, and randomized classes respectively. See diagram in figure 13.

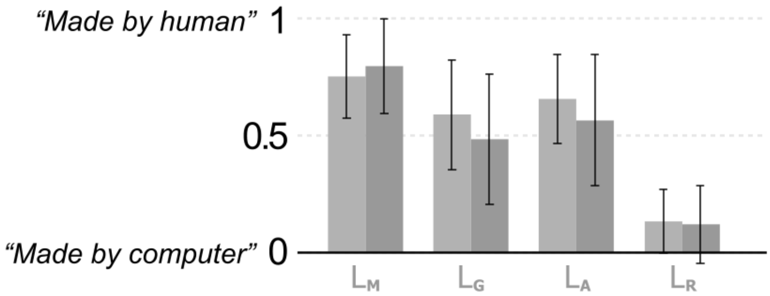

Figure 13. Diagram showing plausibility rating means (± SD) from 0="Made by computer" to 1="Made by human" for the manual (L_M), generated (L_G), generated-adjusted (L_A), and randomized layouts(L_R). The lighter columns represent results from the 2-second viewings and the darker columns represent results from the 10-second viewing.

Fisher's exact test was used to compare the binary plausibility responses of the four layout classes. The manual layouts (L_M) were perceived as significantly more plausible ($p < 0.01$) than the other layouts (L_G, L_A, or L_R) for either exposure duration. The randomized layouts L_R were perceived as significantly ($p < 0.01$) less plausible than all other layout classes (L_M, L_G, or L_A) for either exposure duration. The adjusted layouts L_A were perceived as almost significantly more plausible than the generated layouts L_G for the 2-second viewings ($p = 0.052$) and there was a weaker indication for that regarding the 10-second viewings ($p = 0.090$). The plausibility results for the adjusted layouts L_A were significantly ($p = 0.012$) different between exposure durations. The generated layouts L_G were also assessed as significantly ($p < 0.01$) less plausible for the 10-second viewings than for the 2-second viewings. There was however no significant improvement for the manual layouts L_M ($p = 0.110$) or decrease for the randomized layouts L_R ($p = 0.360$) when comparing the 2-second viewings to the 10-second viewings.

Participants only assessed the human-made layouts L_M as such 75% of times and 79% of times for the 2-second and 10-second viewings respectively. The artificial constraints of the designer process outlined in *section 3.4.3.* should be kept in mind.

5.1.1 Per-layout plausibility

Layout class	**Generated (L_G/L_M)**		**Adjusted (L_A/L_M)**		**Randomized (L_R/L_M)**	
Duration:	**2 s**	**10 s**	**2 s**	**10 s**	**2 s**	**10 s**
Room #1 p-value:	**0.009**	0.102	0.785	0.311	**0.000**	**0.000**
Room #2 p-value:	**0.001**	0.102	**0.005**	0.185	**0.000**	**0.000**
Room #4 p-value:	0.822	**0.027**	0.263	0.519	0.061	0.204
Room #5 p-value:	**0.001**	**0.002**	**0.001**	**0.002**	**0.000**	**0.000**
Room #6 p-value:	0.189	0.058	**0.026**	0.212	**0.000**	**0.000**
Room #7 p-value:	0.446	**0.006**	0.785	0.212	**0.000**	**0.000**
Room #8 p-value:	0.592	**0.001**	0.431	**0.003**	**0.000**	**0.000**
Room #9 p-value:	0.370	0.744	1.000	0.736	**0.000**	**0.000**
Sig. diff. count:	**3**	**4**	**3**	**2**	**7**	**7**

Table 2. Chi-square analysis (significance level 0.05) for comparison between plausibility values of the manual layouts L_M compared to the corresponding generated L_G, generated-adjusted L_A, and randomized L_R arrangements of furniture in the same room. P-values shown in boldface indicate significant differentiation. Room #3's layouts were excluded from analysis, as mentioned in section 4.2.

Plausibility answers for the synthetic layouts (L_G, L_A, & L_R) were compared, using chi-square analysis, to those of the corresponding human-made layouts L_M – shown under the same conditions with the same interior objects in the same room. All layouts (L_G, L_A, or L_R) with significantly differentiated results were perceived as significantly less plausible than their corresponding L_M human-made layout, while no significance indicates that participants did *not* perceive those layouts as significantly less plausible than corresponding human-made layouts L_M (see table 2). For the 2-second exposure duration, three of eight generated layouts L_G, three of eight generated-adjusted layouts L_A, and seven of eight randomized layouts L_R were perceived as significantly less plausible than corresponding human-made layouts L_M. For the 10-second exposure duration, four of eight generated layouts L_G, two of eight generated-adjusted layouts L_A, and seven of eight randomized layouts L_R were perceived as significantly less plausible than corresponding human-made layouts L_M.

Note that while there is only *one* significantly less plausible layout (for room #5) common between exposure durations for both generated L_G and adjusted layouts L_A, *two* specific rooms' layouts (for rooms #5 & #8) were perceived as significantly less plausible for the 10-second exposure of both the generated L_G and adjusted layouts L_A.

5.2 Participant consistency

The participants' ability to answer consistently was tested by comparing their answers for the same layouts upon first and second viewing – both 2 seconds under the same condition. The average same-answer frequency (for assessment of human-made vs. computer generated) was 73% with a standard deviation of 10 percentage points. Individual results varied between 61%–89%. There was no notable difference between layout classes.

5.3 Orderliness

The human-made layouts L_M were perceived as being significantly ($p < 0.01$) more orderly than the other layouts (L_G, L_A, & L_R) and the randomized layouts (L_R) as significantly ($p < 0.01$) less orderly than the other layouts (L_M, L_G, & L_A). Perceived orderliness of the generated layouts L_G and generated-adjusted layouts L_A could not be significantly differentiated from each other ($p = 0.123$ for 2s, $p = 0.068$ for 10 s). Orderliness averages consistently ranked (from most to least orderly) from manual L_M to generated-adjusted L_A to generated L_G to randomized L_R (see fig. 14).

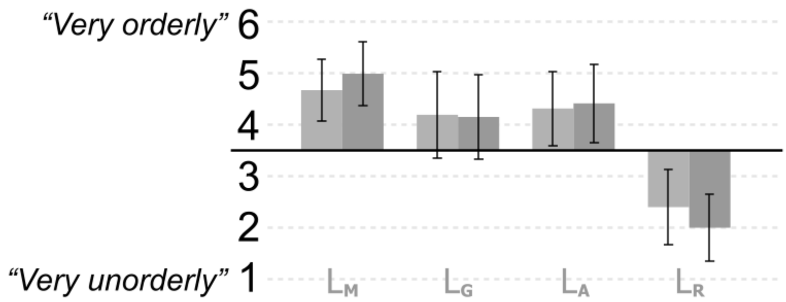

Figure 14. Diagram showing average orderliness rating (± SD) from 1=Very unorderly to 6=Very orderly for the manual (L_M), generated (L_G), generated-adjusted (L_A), and randomized layouts (L_R). The lighter columns represent results from the 2-second viewings and the darker columns represent results from the 10-second viewing.

There was no (within 95% confidence interval) correlation between orderliness values and exposure duration. Perceived orderliness was positively correlated with perceptual plausibility ($p < 0.05$), except for the randomized layouts L_R when viewed for 10 s ($p = 0.528$). Correlation was investigated by comparing perceived orderliness values of layout viewings in which the participant assessed them as made by a human with those assessed as made by a computer. All paired orderliness data sets were tested for significant differentiation using Wilcoxon signed-rank test.

5.4 Interpretation of potential habitation

Overall, 67% of the layout viewings received responses that the room seemed lived-in rather than part of a show house. There was little variation between layout classes or exposure times with means deviating less than 10 pp from the overall mean (see fig. 15). Nevertheless, it became apparent that many participants had difficulty fully comprehending the question and many commented that neither of the possible answers were appropriate.

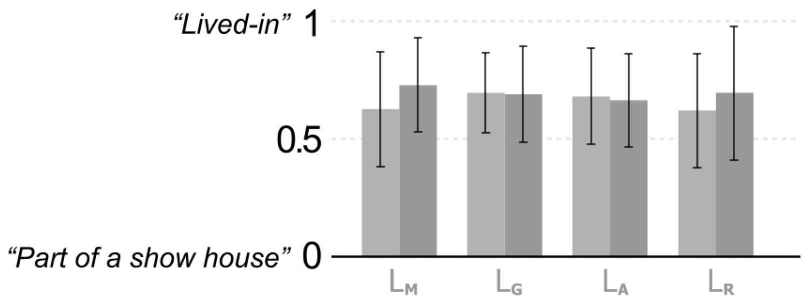

Figure 15. Diagram showing layout interpretation means (± SD) from 0="Part of show house" to 1="Lived-in" for the manual (L_M), generated (L_G), generated-adjusted (L_A), and randomized layouts (L_R). The lighter columns represent results from the 2-second viewings and the darker columns represent results from the 10-second viewing.

Following Fisher's exact test, there was no statistical difference (within 95% confidence interval) between classes of layouts for the 10-second viewings. Regarding the 2-second viewings, the generated layouts L_G were rated significantly more as lived-in than the randomized layouts L_R ($p = 0.028$) and the manual layouts L_M ($p = 0.040$); apart from that there were no significant differences between layout classes. Manual layouts L_M were perceived significantly ($p < 0.01$) more as lived-in layouts for the 10-second viewings than for the 2-second viewings. Randomized layouts L_R were also perceived significantly ($p = 0.028$) more as lived-in layouts for the 10-second viewings than for the 2-second viewings. There was no significant difference for values between exposure times for the generated L_G and adjusted layouts L_A.

5.5 Cues of computer generation

The randomized layouts L_R were often simply described as chaotic or that "the chairs were all over the place". Most valuable comments on specific artificial-looking features came after viewing the layouts of the manual L_M, generated L_G, and generated-adjusted L_A classes, and are described below.

5.5.1 TV

Participants paid great attention to the position of the TV set. The TV was mentioned for 34% of the layouts shown (see table 3). Many participants were critical when there was a substantial distance between the TV and the wall (see fig. 15) (C_{14}). One rationalization suggested by the participants for having the TV away from the wall, was to counteract poor eyesight. Space behind the TV enabled the algorithm to place objects behind it. For the generated layout L_G with a plant behind the TV and its adjusted version L_A (plant still behind TV), 60% of participants expressed that it was unnatural that there was a plant behind the TV. One of the designer-made L_M layouts also had a plant behind the TV, and 35% of participants remarked on this. One participant mentioned that the reason could be in order to obscure backlight from the windows in that layout.

Object	Mentions	Object	Mentions	Feature	Mentions
TV set	216	Piano	38	Wall	94
Table	135	Plant	33	Door	55
Sofa	117	Wall picture	21	Window	22
Chair	78	Shelf	20	Wallpaper	5
Armchair	45	Cabinet	5	Ceiling light	2

Table 3. Table with number of layout viewings (in total 640) for which the respective objects or features were mentioned. Not all objects were present in all layouts shown.

There were five remarks on sofa-TV misalignment for the generated layouts L_G, but only one such remark for the adjusted layouts L_A where the TV was adjusted (C_7 adjustment) to always be aligned centrally to the main sofa seating area. For the generated layouts L_G, the TV was not aligned in that way in relation to the corner sofa specifically (C_7).

5.5.2 Chairs around table

Following its rules for placing related furniture, the algorithm placed chairs evenly around the sides of a table, even when the dining table's long sides could accommodate all chairs. There were eight remarks about these table-chair configurations (C_9) for the generated layouts L_G. There were no remarks about the table-chair configurations in the manual layouts L_M, or in the generated-adjusted layouts L_A where they were adjusted to the conventional placement around such a dining table. There were also six remarks about the chairs not being pushed in under the table for the generated layouts L_G, but none for the generated-adjusted layouts L_A even though the distance between the table edge and chairs was the same. Curiously, the manual layouts L_M received five remarks about this.

The generated L_G and generated-adjusted layouts L_A received 20 remarks about tables and chairs possibly bumping into other furniture such as the TV when there was not much space behind the chairs. Overall, there were two remarks about dining tables not being pushed in towards the wall (C_{10}) and two positive comments about a table side being along the wall.

5.5.3 Obstruction and closeness to door

75% of the manual layouts L_M and generated L_G and generated-adjusted layouts L_A received remarks on excessive closeness of objects to other objects or doors (C_{13}, C_{15}, and other, unadjusted cues). 44% of the generated L_G and generated-adjusted layouts L_A received remarks on furniture generally obstructing, or being in the way of the flow between doors or between parts of the room. This only occurred for one of the manual layouts L_M.

5.5.4 Functional break-up

Participants expressed consideration for the function of furniture and the functional relations between furniture. For example, they commented when sofas and armchairs were placed separately in different parts of the room, and when the armchair was not positioned towards the TV (see fig. 16). 51% of participants commented about an armchair being placed separately from the sofa for the generated L_G and generated-adjusted layouts L_A when that was the case. 45% also commented on that for the L_M manual layout when that was the case. Some specific comments about the randomized layouts L_R involved concerns about tables without chairs and TVs without seating furniture.

Figure 16. Generated layout with substantial distance to wall behind TV (left) and generated layout with armchair not positioned towards TV (right).

5.6 Points of interest

In this chapter, the results from both the questionnaire (see *sections 5.1*, *5.3*, & *5.4*) and think-aloud sessions (see *section 5.5*) have been described and statistically analysed when appropriate. The randomized semi-arbitrary layouts L_R were significantly less plausible than all other evaluated layouts (L_M, L_G, & L_A). The manual layouts L_M were the most plausible as expected, but the adjustments to the generated layouts did not prove to increase the plausibility of the adjusted layouts significantly. The generated L_G and generated-adjusted layouts L_A were less plausible when viewed for 10 seconds than for 2 seconds (see *section 5.1*). It was also found that perceived orderliness was mostly positively correlated with perceived plausibility as hypothesized (see *section 5.3*). Possible interpretations of the results are discussed in the next chapter.

6 Discussion

Qualitative data and quantitative data with statistics were presented in the previous result chapter. Possible explanations and observed effects are discussed in this chapter. The main purpose of this project was to investigate how plausible human-made layouts L_M and layouts generated by a side-based spatial relation constraint algorithm L_G are perceived and what aspects affect plausibility. Perceived orderliness was found to significantly ($p < 0.05$) correlate with whether layouts were perceived as plausible, except for semi-arbitrarily randomized layouts L_R shown for a longer 10-second duration.

The randomized layouts L_R were assessed to be computer-made as often for either exposure duration. Whereas they were exposed as being computer-made even at a short glance, the layouts generated by the side-based spatial relation constraint algorithm L_G received much more favourable results. While not perceived as plausible as often as the human-made layouts L_M, even the human-made layouts L_M were only perceived as such in 76% of the cases. The adjustments to hide the supposed cues for computer-generation caused other artefacts that participants remarked on, and the adjusted layouts L_A did not clearly yield significantly better results than the unadjusted computer-generated layouts L_G. Under more occluded conditions, the generated layouts L_G may not as often be perceived as implausible. Depending on the application, layouts generated by a side-based relation constraint algorithm may suffice.

Participants paid particular attention to the distance of the TV from the wall (C_{14}) and its placement in relation to other furniture. Layouts including placement of the sofa and armchair in different areas of the room were often perceived as computer made.

6.1 Virtual environment

If the experiment had been conducted using a VR HMD (Head-mounted display), participants would receive different stimuli, as they would move their heads differently during the experiment. It was also expected to have taken more time to conduct the experiment, which could strain the participants. Layouts were viewed by the author in a prototype developed for *Google Cardboard* VR HMDs. Exact object placements were more easily perceptible in the VR prototype, which supported walking around inside the virtual rooms, than from the outside perspective presented on a normal 2D screen. However, heavy rendering load caused stuttering performance when looking around, which caused discomfort after a few minutes.

6.2 Saliency of affordances

It could be assumed that available actions are not as saliently perceived when viewing furniture in a scene presented on a 2D screen, compared to if the participants were immersed in the environment using a VR HMD or if they were physically situated in an actual room. This may have affected how they perceived and evaluated the layouts. Virtual environments that offer meaningful interactions and walkthrough experiences offer greater attention to social amenities, accessibility, and functionality (Kort et al., 2003). Also, it could be reasoned that the adjusted layouts L_A and generated layouts L_G were perceived as significantly less plausible when viewed for the longer duration since it gave participants time to process scene details more thoroughly (see *section 2.3.1*).

6.2.1 Inhabitants and functionality

The question about whether the participants interpreted the room as inhabited or not was phrased in a way that seemed to be poorly understood by study participants. It is therefore difficult to gauge the quality of the data. Generally, the responses tended to classify the layouts as "lived-in" rather than "part of a show house". The significant answer differences between exposure durations for the manual L_M and randomized layouts L_R could be connected to the participants interpretation of (virtual) inhabitants. Since the longer viewings gave the participants more time to process details and the ability to move right and left back-and-forth to inspect the layouts, one can assume they noticed more aspects of the layouts and had more time to reason. They remarked heavily on the shortcomings of the randomized layouts L_R, but many offered the explanation that the layout could have been made messy by for example children playing there which would lead to a conclusion that the layout must be lived-in. This could also explain the lack of correlation between perceived orderliness and plausibility for only the randomized layouts L_R viewed for 10 seconds. Perhaps the participants also understood the functionality of the human-made layouts better after the 10-second viewings and thought they worked well as lived-in layouts. Per-layout plausibility analysis (see *section 5.1.1*) indicated that for different viewing durations, not the same synthetic layouts (L_G & L_A) were perceived as significantly less plausible than the human-made layouts L_M. This could be connected to viewing-time dependant visual processing modes, as described in *section 2.3.1*.

6.3 Missing algorithm considerations

As many aspects and considerations of interior design were not emulated by the furniture layout generation algorithm, this negatively affected the perception of the produced layouts.

6.3.1 Variable distances and wall constraints

If a placement unit included objects with constraints regarding set distances to walls in opposite directions, one of the constraints was ignored as both could only be satisfied if the distance between their endpoints matched the distance between the walls of the room. The fixed distance defined between objects yielded poor results for the sofa-TV unit, with many participants saying that the distance between the TV set and wall was implausible (C_{14}). Set distances are therefore not suitable for such arrangements. The plausibility would probably improve if the algorithm could enforce wall constraints for both the back of the sofa and of the TV as long as the distance was within a defined interval.

6.3.2 Conventional chair-table arrangement

Arrangement of chairs around tables is fairly rigid and simple; there are only a limited number of configurations that work well (Rengel, 2012). This algorithm only replicates the typical arrangement of chairs around *square* tables. Participants commented that chairs were not all placed by the broad side of the oblong tables (C_9), even though those sides could accommodate them (see fig. 17). Chairs are typically placed concentrically around circular tables (Rengel, 2012), but furniture could only be defined as rectangles. Since the conventional placement is rigid and viewers did notice the chair-table configurations, a special procedure could be programmed for chair-table placement.

6.3.3 Balance

Balance of furniture around the centroid of the room and around furniture groups was not part of the algorithm, as in other algorithms such as the one by Merrell et al. (2011) described in *section 2.2.1*. This gave rise to comments saying generated layouts were “unbalanced” or “without balance”.

6.3.4 Flow

While furniture had defined clearance areas around them, there was no specific consideration of furniture placements potentially blocking circulation routes such as natural paths between doors. A few participants remarked on furniture obstructing the flow between parts of the room and rooms looking cramped. No furniture in the generated layouts was inaccessible by walking on the floor. In contrast, Germer and Schwarz (2009) observed that 37% of layouts generated by their algorithm – which only fulfilled side-based spatial relation constraints and overlap constraints and did not implement any clearance area constraints or other accessibility constraints – included obstructed or inaccessible interior objects.

6.3.5 Other arrangement aspects

Many interior projects have repeating units (such as dining tables with chairs in a restaurant) that may be arranged in clusters or rows. Furniture groups are often aligned by their edges or centres. Large rooms often house multiple furniture groups (Rengel, 2012) but the rooms in this experiment were not that large. There were no remarks on lack of centring or alignment (aside from TV-sofa alignment, see *section 5.5.1*) despite the algorithm only centring furniture within groups. To reduce window blockage, the algorithm did not place any tall objects, such as bookcases or cabinets, by windows even though that could be appropriate for narrow objects or plants requiring sunlight (C_3).

6.3.6 Tool-user mistakes

Not enough care was taken when entering clearance area values for all furniture. The chairs did not have enough defined clearance area *behind* them to guarantee ability to fully pull them out from a table. That caused layouts where the chairs would bump into other furniture when pulled out, and study participants remarked on that.

6.4 Over-analytical thinking

Effort was made to de-emphasize participant performance when the task of assessing if layouts were made by a human or computer was phrased. However, it is assumed that many experiment participants felt pressure to perform well, since many of them expressed some anxiety over whether they would be “good enough” at the assessment tasks. This could have made them over-critical, and made some expect everything except very conventional layouts to have been created by a computer. Conversely, some participants seemed to mostly believe only the semi-arbitrary randomized layout L_R were made by a computer. The intention was to capture their automatic response to the layouts, but automatic cognition relies on formed schemas (DiMaggio, 1997) and schema-driven cognition generalizes. Once a schema has been triggered by seen features, it guides thought, filtering away irrelevant information, and can lead to faulty judgments (Stillings et al., 1995).

Figure 17. Generated layout with unconventional configuration of chairs around dining table (left). Human-made layout in room #4 where the armchair is intentionally placed separately in a reading corner and the sofa is intended for watching TV (right).

The unfamiliar assessment task required them to construct their own assessment criteria. Subsequent layout responses seemed to be biased by such assessment schemas that emerged from viewing previous layouts. Examples of such an emergent assessment criterion might be “occurrence of separate sofa–armchair”. There was no “draw” in the creation of the generated L_G, adjusted L_A and randomized layouts L_R for placing armchairs and sofas together. They were therefore placed apart more often in those layouts, which on average were rated less human-made than the manual layouts L_M. It seemed as if those facts were connected in the assessment schema so the separated armchair-sofa placements apparently became an attribute for computer generated layouts, as if only the computer disregarded placing the armchair and sofa together. In L_M layout #4 by the human designer there was an armchair in the opposite corner of the room compared to the sofa (see fig. 17). While the separate armchair with a floor lamp was intended as a “reading corner”, it scored lower than other manual layouts and many said that the separation made no sense.

One issue that needs to be raised is to what extent the participants used automatic cognition versus deliberate cognition. If people were to see interior objects behind windows in the virtual environment of a driving simulator, one could assume that they would not deliberately try to figure out if the objects were placed manually or according to an algorithm.

The explanation of the situation “looking in through windows” was included so that the study participants would not see the assessment task as *problem solving*, which easily makes people shift into deliberate modes of thought (DiMaggio, 1997). As participants were encouraged to think aloud while viewing and answering, they would often verbalize their thoughts which was useful for analysis but could have led them to rely more on deliberate cognition, which is verbalized (DiMaggio, 1997). On the other hand, using *retrospective think-aloud protocols* instead by having participants explaining and formulating their reasoning *after* performing the tasks could lead to inaccurate hindsight rationalization (Van Den Haak et al., 2003). Finally, lacking schemas does incite deliberate cognition (DiMaggio, 1997), which is likely the initial state upon encountering an unfamiliar classification task. Participants were given a chance to build cognitive models of the assessment task during the two practice layout viewings, but future research would probably improve with more extensive participant familiarization of virtual layout assessment.

6.5 Performance problems

While placing a set of furniture in a spacious room was usually completed by the algorithm in less than a second on a 2.5 GHz *Intel Core i7* PC, more constrained spaces could in some cases increase the algorithm’s processing time exponentially. This was the case for two of the layouts, in which a couple of interior objects were removed from the manual layouts L_M to enable the execution of the algorithmic rearrangement within a reasonable timeframe. The problem was due to the unoptimized geometric placement constraint solver algorithm used for placing the placement units after they were assembled. It increased in computational complexity quadratically with the raster size of available room placements and exponentially with the number of placement units to be placed. Nevertheless, real-time performance was not targeted or attempted in the project.

6.6 Comparison to sophisticated algorithm

Yu et al. (2011) also performed per-layout chi-square analysis of their synthetic layouts and human-made layouts to find significant differences. Their more sophisticated optimization-based furniture arrangement generation algorithm layouts were perceived significantly differently in terms of preference for just three of 21 layouts; whereas the generated layouts L_G in this work were perceived as significantly less plausible for three or four layouts of eight for the 2-second and 10-second exposures respectively (see *section 5.1.1*). However, the fastest runtime to generate one layouts in Yu et al.’s algorithm was as much as 22 seconds on a 3.33 GHz *Intel Xeon* PC.

6.7 Future work

If deterministic furniture layout generation is to be used as in this project, it would be advisable to use an efficient geometric placement constraint solver for the sake of good performance. Algorithms designed for parallelization of for example layout constraint solving as used by Merrell et al. (2011) would greatly benefit from the new hardware with thousands of compute cores. Increased efficiency afforded by such leaps in performance could make more sophisticated algorithms feasible. If a highly refined algorithm were able to arrange any clutter, furniture, and other interior objects, it could be used to rearrange virtual replications of authentic rooms and be used in a direct comparison, circumventing the artificiality caused by restrictions on the human designer in this project.

In this project, plausibility was found to be positively correlated with perceived orderliness (see *section 5.3*), but actual real-world interiors can be messy. It would be interesting to test different algorithms for making furniture layouts appear unorderly but still plausible. Perhaps furniture disarrangements based on simulated hasty agent movement through the room would result in more plausible unorderly layouts than furniture with positions and orientations simply perturbed, as in the Germer and Schwarz (2009) algorithm. If a more plausible type of unorderliness were to be found, a possible upper threshold for plausible unorderliness could also be investigated. Furthermore, clutter and disarranged items are another dimension of orderliness perception to be taken into account.

The user situation is different depending on the specific simulator, game, or other application and display method (stationary screen, VR HMD, AR device, etc.) and this affects the way the user experiences the layouts regarding affordances. It would therefore be more accurate to measure perceptual plausibility in the specific context in which the user would experience it. In this project, evaluation was only done on perception of layouts from first-person perspective through windows. Even as the prevalence of virtual environments increases, there is still limited research of them in the field of environmental psychology. Better insight could lead to more informed designing of good virtual environments.

6.8 Towards conclusion

This chapter discussed confounding issues that could potentially bias the evaluation of furniture layouts in virtual environments (see *sections 6.2* & *6.4*). The layout generation algorithm of this work compared disfavourably to a more sophisticated algorithm in evaluation of plausibility (see *section 6.6*). Identified deficiencies of the algorithm were discussed in *sections 6.3* and *6.5*. The next chapter summarizes the main findings of this work and points to possible future developments.

7 Conclusion

The plausibility evaluation of furniture layouts in virtual space showed that having only side-based spatial relation constraints and clearance area constraints in a furniture placement algorithm improved perceptual plausibility significantly versus arbitrary placement of furniture with only wall-placement constraints for relevant furniture, which was hypothesized (for SO_3). The procedural layout generation algorithm produced layouts that were perceived to be significantly less plausible than the layouts made by a human interior designer, as hypothesized for research question. However, the human-made layouts were only perceived as such in 76% of the cases, whereas the generated layouts were perceived as human-made in 55% of cases. Generated and adjusted layouts were significantly more perceptually plausible when viewed for 2 seconds than when inspected for 10 seconds. The layouts adjusted to hide researcher observed cues of synthetic generation were not significantly more plausible than the unaltered generated layouts, thus failing to confirm that hypothesis (for SO_2).

The perceived orderliness of the generated layouts was found to be positively correlated with their plausibility, in accordance with the hypothesis (for SO_1). All layouts were on average assessed to be more orderly than unorderly, except the semi-arbitrary layouts which were deemed more unorderly. Missing considerations in the simple algorithm – such as visual balance, circulation, and ergonomics – did cause apparent deficiencies in the generated layouts. Several salient cues for procedural generation could be identified and demonstrated in the evaluation, such as cases where the TV set was placed at considerable distance from the wall or where chairs are placed in an unconventional arrangement around a table.

If layouts are to be presented as background set-pieces behind façades and will not attract much attention, it is possible that a simple algorithm only enforcing physical, clearance area, and side-based relation constraints could generate layouts of sufficient plausibility level. However, for high-fidelity scenes that should withstand closer inspection, development of more sophisticated algorithms is recommended. It will be important to scientifically establish the goals for successful interior designs for each application to inform the design of a good algorithm. Environmental psychologists could incorporate virtual technologies in their research of how interiors impact humans. The development of tensor processing units and graphics processing units with many compute cores may encourage design of more mature and faster parallelized algorithms for furniture layout generation. When procedural generation of interior design becomes refined enough it should be able to replace much of human interior design work in the future. However, it could be difficult to quantify the emotions and aesthetics of the interior designer process, and some design work will thus not be easy to replicate.

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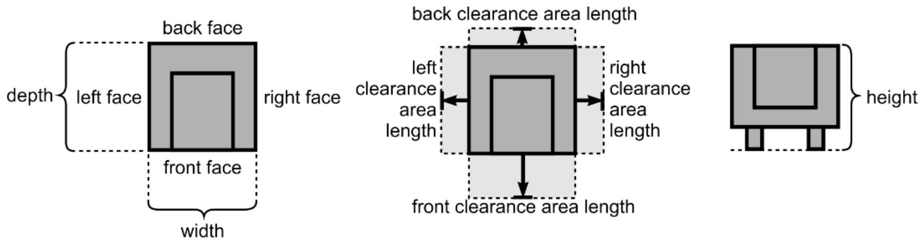
9 Appendices

Interior object data

Object measurements



Object type	Width	Depth	Height	Front face type/ Clearance area length	Back face type/ Clearance area length	Left face type/ Clearance area length	Right face type/ Clearance area length
Chair	0.50 m	0.62 m	1.18 m	chair front 0.30 m	chair back 0.25 m	chair lateral side 0.10 m	chair lateral side 0.10 m
Chair	0.42 m	0.48 m	0.89 m	chair front 0.30 m	chair back 0.25 m	chair lateral side 0.10 m	chair lateral side 0.10 m
Table	1.24 m	1.24 m	0.75 m	table side	table side	table side	table side
Table	1.70 m	0.90 m	0.75 m	table side	table side	table side	table side
Stool	0.44 m	0.39 m	0.41 m	stool front 0.10 m	stool back 0.10 m	stool lateral side 0.10 m	stool lateral side 0.10 m
Sofa	1.70 m	0.90 m	0.80 m	sofa front 0.30 m	sofa back	sofa lateral side	sofa lateral side
Sofa	2.28 m	0.97 m	0.77 m	sofa front 0.30 m	sofa back	sofa lateral side	sofa lateral side
Corner sofa	2.49 m	1.90 m	0.78 m	sofa front 0.30 m	sofa back	sofa back	sofa lateral side 0.30 m
Armchair	0.96 m	0.85 m	0.79 m	armchair front 0.30 m	armchair back	armchair lateral side	armchair lateral side
Armchair	0.56 m	0.55 m	0.88 m	armchair front 0.30 m	armchair back	armchair lateral side	armchair lateral side
Armchair	0.58 m	0.68 m	0.95 m	armchair front 0.30 m	armchair back	armchair lateral side	armchair lateral side
Foot Stool	0.60 m	0.51 m	0.33 m	foot stool front	foot stool back	foot stool lateral side	foot stool lateral side
Coffee table	1.24 m	0.52 m	0.48 m	coffee table long side 0.25 m	coffee table long side 0.25 m	coffee table lateral side 0.25 m	coffee table lateral side 0.25 m
Side table	0.42 m	0.35 m	0.42 m	side table side	side table side	side table side	side table side
Floor lamp	0.40 m	0.40 m	1.43 m	floor lamp side	floor lamp side	floor lamp side	floor lamp side
TV	1.04 m	0.22 m	0.85 m	tv front 1.80 m	tv back	tv lateral side	tv lateral side
Bookcase	1.43 m	0.56 m	1.98 m	bookcase front 0.80 m	bookcase back	bookcase lateral side	bookcase lateral side
Bookcase	0.45 m	0.45 m	1.61 m	bookcase front 0.80 m	bookcase back	bookcase lateral side	bookcase lateral side
Bookcase	1.09 m	0.44 m	1.78 m	bookcase front 0.80 m	bookcase back	bookcase lateral side	bookcase lateral side
Cabinet	0.73 m	0.41 m	1.17 m	cabinet front 1.00 m	cabinet back	cabinet lateral side	cabinet lateral side
Cabinet	1.11 m	0.37 m	1.22 m	cabinet front 0.80 m	cabinet back	cabinet lateral side	cabinet lateral side
Sideboard	1.69 m	0.55 m	0.51 m	sideboard front 0.80 m	sideboard back	sideboard lateral side	sideboard lateral side
Wall picture	0.73 m	0.07 m	1.80 m	wall picture front 0.80 m	wall picture back	wall picture lateral side	wall picture lateral side
Wall picture	0.75 m	0.01 m	1.70 m	wall picture front 0.80 m	wall picture back	wall picture lateral side	wall picture lateral side
Wall picture	0.50 m	0.01 m	1.60 m	wall picture front 0.80 m	wall picture back	wall picture lateral side	wall picture lateral side
Wall picture	0.24 m	0.01 m	1.63 m	wall picture front 0.80 m	wall picture back	wall picture lateral side	wall picture lateral side

Wall picture	0.20 m	0.01 m	1.59 m	wall picture front 0.80 m	wall picture back	wall picture lateral side	wall picture lateral side
Wall picture	0.20 m	0.01 m	1.59 m	wall picture front 0.80 m	wall picture back	wall picture lateral side	wall picture lateral side
Wall picture	0.20 m	0.01 m	1.59 m	wall picture front 0.80 m	wall picture back	wall picture lateral side	wall picture lateral side
Wall picture	0.20 m	0.01 m	1.59 m	wall picture front 0.80 m	wall picture back	wall picture lateral side	wall picture lateral side
Electric guitar	0.35 m	0.33 m	1.10 m	electric guitar front 0.80 m	electric guitar back	electric guitar lateral side	electric guitar lateral side
Piano	1.32 m	1.48 m	1.03 m	piano keyboard side 0.90 m	piano back 0.05 m	piano lateral side 0.05 m	piano lateral side 0.05 m
Piano bench	0.62 m	0.36 m	0.53 m	piano bench front 0.40 m	piano bench back	piano bench lateral side	piano bench lateral side
Floor plant	0.83 m	0.81 m	1.64 m	floor plant side 0.10 m	floor plant side 0.10 m	floor plant side 0.10 m	floor plant side 0.10 m
Floor plant	0.38 m	0.37 m	1.40 m	floor plant side 0.10 m	floor plant side 0.10 m	floor plant side 0.10 m	floor plant side 0.10 m
Floor plant	0.61 m	0.56 m	1.41 m	floor plant side 0.10 m	floor plant side 0.10 m	floor plant side 0.10 m	floor plant side 0.10 m
Floor plant	0.37 m	0.45 m	1.09 m	floor plant side 0.10 m	floor plant side 0.10 m	floor plant side 0.10 m	floor plant side 0.10 m
Urn	0.47 m	0.47 m	0.78 m	urn side 0.10 m	urn side 0.10 m	urn side 0.10 m	urn side 0.10 m
Football table	1.51 m	1.26 m	1.02 m	football table goal side 0.50 m	football table goal side 0.50 m	football table play side 0.05 m	football table play side 0.05 m
Pool table	2.59 m	1.40 m	0.83 m	pool table broad side 0.55 m	pool table broad side 0.55 m	pool table end side 0.55 m	pool table end side 0.55 m
Wall box	0.26 m	0.16 m	1.50 m	wall box front 0.80 m	wall box back	wall box lateral side	wall box lateral side
Wall box	0.30 m	0.16 m	1.40 m	wall box front 0.80 m	wall box back	wall box lateral side	wall box lateral side
Wall shelf	1.00 m	0.22 m	1.60 m	wall shelf front 0.80 m	wall shelf back	wall shelf lateral side	wall shelf lateral side
Wall shelf	1.00 m	0.22 m	1.60 m	wall shelf front 0.80 m	wall shelf back	wall shelf lateral side	wall shelf lateral side

* Window dimensions: (w: 0.9 m, d: 0.2 m, h: 1.5 m) & 0.8 m elevation. Clearance area inward length: 0.9 m.
* Door dimensions: (w: 0.9 m, d: 0.25 m, h: 2.1 m). Clearance area inward length: 0.9 m.

Pair-wise object face relations

- 'chair front' at 0 m distance from 'table side'
- 'stool front' at 0.20 m distance from 'table side'
- 'sofa lateral side' at 0.10 m distance from 'side table side'
- 'sofa back' at 0 m distance from 'wall'
- 'sofa front' at 0.25 m distance from 'coffee table long side'
- 'armchair back' at 0.10 m distance from 'wall'
- 'foot stool back' at 0.05 m distance from 'sofa front' or at 0.05 m distance from 'armchair front'
- 'floor lamp side' at 0.20 m distance from 'sofa lateral side' or at 0.20 m distance from 'armchair lateral side'
- 'tv front' at 1.80 m distance from 'sofa front'
- 'bookcase back' at 0 m distance from 'wall'
- 'cabinet back' at 0 m distance from 'wall'
- 'sideboard back' at 0 m distance from 'wall'
- 'wall picture back' at 0 m distance from 'wall'
- 'electric guitar back' at 0.10 m distance from 'wall'
- 'piano bench front' at 0.25 m distance from 'piano keyboard side'
- 'floor plant side' at 0.10 m distance from 'wall'
- 'urn side' at 0.10 m distance from 'wall'
- 'wall box back' at 0 m distance from 'wall'
- 'wall box lateral side' at 0.10 m distance from 'wall box lateral side'
- 'wall shelf back' at 0 distance from 'wall'

Consent form for study of virtual furniture layouts perception

You are invited to take part in a research study of how object layouts within virtual rooms are perceived. Please read this form carefully and ask any questions you may have before agreeing to take part in the study.

What the study is about: The purpose of this study is to learn how people perceive interior layouts of objects in virtual rooms by allowing them to view them under controlled circumstances. Some of the layouts have been made by a human and some by a computer.

What we will ask you to do: If you agree to be in this study, we will ask you to sit at a computer and click through an interactive viewing program, following its instructions. The test will be divided into two sections. As you go through the tasks of the second section, I would like you to think out loud about your reasoning for answering the way you do. It is important to know that I am testing how the layouts are perceived and not your abilities in any way. I may ask you additional questions about your interpretation or perceptions of the layouts you see.

Risks and benefits: I do not anticipate any risks to you participating in this study other than those encountered in day-to-day life. There are no benefits to you other than the compensation stated below.

Compensation: A box of chocolates.

Taking part in this study is completely voluntary. You may skip any tasks that you do not want to complete or attempt, without stating why. If you decide to take part, you are free to withdraw at any time, without stating why.

In any sort of report I make public I will not include any information that will make it possible to identify you. Research records will be kept in a password-locked computer; only researchers will have access to the records.

If you have questions: The study leader conducting this is David Ringqvist. Please ask any questions you have now. If you have questions later, you may contact me at time at [email address].

You will be given a copy of this form to keep for your records.

Statement of Consent: I have read the above information, and have received answers to any questions I asked. I consent to take part in the study.

Your Signature ______________________________ Date _________________

This consent form will be kept by the researcher for at least three years beyond the end of the study.

Participant info

Please fill out this form. All data will be anonymized.

Eyesight (After correction with glasses, if worn now):
❑ Normal vision ❑ Significantly impaired screen-viewing

Interior layout experience:
❑ None ❑ Personal experience ❑ Professional experience

3D game playing experience *(Or any non-game virtual 3D environment navigation)***:**
❑ None ❑ Have navigated virtual 3D environments

Age:

____

Sex:
❑ Female ❑ Male ❑ Other/Unspecified

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