# Integrating Virtual Reality During the Architectural Design Process: a Survey to Identify Practitioner Needs

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**Abstract**
In recent years, an increasing number of tools and systems targeting the integration of immersive technologies in architectural practice have been developed. Architectural firms have increasingly been adopting them, especially Virtual Reality (VR), but the technology is mainly employed as a means to showcase their finished projects to prospective clients. We posit that the use of the technology should be integrated as part of the design process itself. To verify that claim, we conducted an online survey on the potential of using VR for architectural design. We gathered 36 responses, that were contrasted with potentially influential factors such as the respondent's prior experience with VR devices. We conclude that there is indeed a demand for a more complete integration of VR technology in architectural practice. We also investigated how VR could be employed for Algorithmic Design (also known as Parametric Modelling) and we put our findings in perspective with existing work. By sharing these findings, we hope to accelerate future efforts towards integrating VR solutions in the architectural and urban design process to address the needs identified through this survey.

**Keywords:** Architectural Design, Virtual Reality, Algorithmic Design, Parametric Modelling

## 1 Introduction

Ever since its conception in the middle of the 20th century, Computer-Aided Design (CAD) has undergone drastic conceptual and technical improvements. Designers from many domains have benefited from this evolution, thanks to an ever-improving tool suite becoming available to them.

Visualisation is one of the key CAD features that has seen dramatic improvements, with three-dimensional and photorealistic renderings becoming commonplace in modern CAD systems.

Immersive technologies are also reaching maturity, as can be witnessed by a recent surge in their use due to a significantly improved affordability. As for Virtual Reality (VR) in particular, several head-mounted displays capable of full three-dimensional tracking (positional and rotational tracking, with six degrees of freedom) have become available at a reasonable cost.

Architectural design has followed pace in this evolution, and a number of VR-enabled software systems are now available for architects. These VR systems tackle multiple steps of the design process and most -if not all- popular software suites amongst practitioners are covered to some extent, with newer versions offering better integration and usability of the technology.

A recent study has pointed out that architectural design research tends to exclude practitioners from the loop to validate proposed VR prototypes (Stals & Caldas 2020). We posit that the use of such immersive technologies should be integrated as part of the design process itself. To evaluate architects' opinion on the matter, we conducted a survey with practitioners in architectural design on the potential of integrating VR solutions in their field.

## 2 Methods

The survey took the form of an online questionnaire that was available in two languages: French and English. The questionnaire was shared in January 2020 to a varied audience: practitioners on the Rhinoceros fora (discourse.mcneel.com), researchers on the official eCAADe LinkedIn and Facebook pages; and architecture students from three French-speaking universities (hence the need to have a French version of the questions). We received 80 responses, of which 36 were complete. This article reports on those complete responses. A copy of the questionnaire and the results we gathered can be found online (zenodo.org/record/4696074). The code we used to analyse that data and produce figures is also available online (zenodo.org/record/4696071).

### 2.1 Age profile

Due to the diversity of venues that were targeted to distribute the questionnaire, we obtained a population of respondents with very different age profiles. Figure 1 shows the age distribution amongst the respondents, highlighting that 25 out of 36 participants (69%) were between 20 and 29 years inclusive (median: 25, interquartile range: 9.25). One respondent of age 69 is not shown in the figure because no gender information was reported.

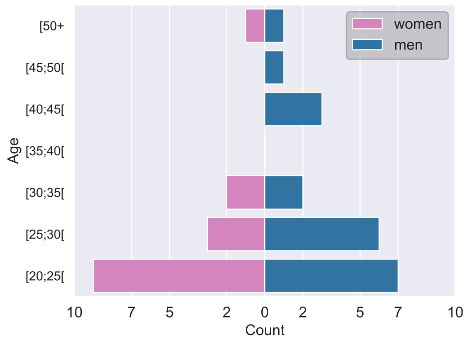


**Figure 1.** Respondents' population pyramid

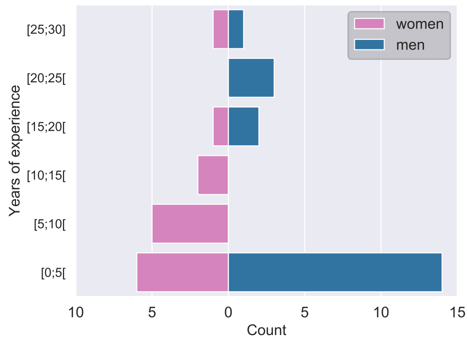


**Figure 2.** Respondents' distribution of experience

### 2.2 Architectural profile

Figure 2 presents the distribution of experience amongst respondents through a population pyramid reporting the number of years of experience in architecture or related fields (median: 3, interquartile range: 8.5) on the Y axis. Figures 1 and 2 seem to suggest that a significant part of our population is comprised of students and recently graduated practitioners. The respondent of unknown gender indicated having no experience in architecture.

The architectural experience, combined with the diplomas reported by respondents allowed us to categorise them into four distinct profiles, presented in Table 1.

**Table 1.** Architectural profiles descriptions

| Architectural profile | Description |
|---|---|
| **Expert (12 respondents)** | Having acquired a Bachelor's degree and 10 years of professional experience; or a Master's Degree and 5 years of professional experience; or a PhD degree. |
| **Competent (11 respondents)** | Having acquired either a Bachelor's degree and one year of professional experience; or a Master's degree. |
| **Novice (11 respondents)** | Currently a Bachelor student, or no (ongoing) diploma but a bit of professional experience. |
| **Uninitiated (2 respondents)** | None of the above apply. Respondents are essentially considered as having no background in the field. |

Figure 3 reveals a balanced grouping of respondents according to their architectural experience. Since the survey targeted architectural practitioners, the **Uninitiated** profile contains only two respondents. We observe a good gender balance across all other architectural profiles. The least balanced profile is **Competent** with a proportion of 63.6% male respondents.

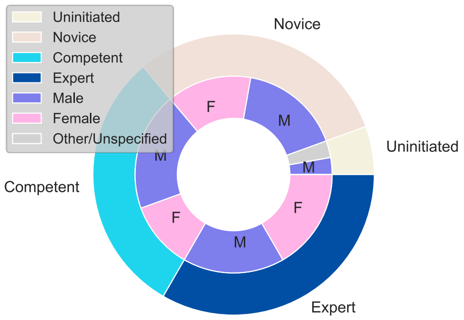


**Figure 3.** Distribution of architectural profiles

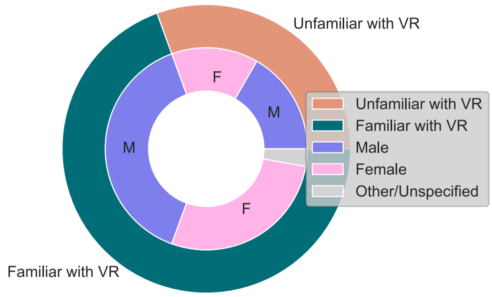


**Figure 4.** Familiarity to VR amongst respondents

## 2.3 Virtual Reality profile

As our survey focuses on the use of VR during the architectural design process, an important aspect to investigate is the familiarity of respondents with VR technology.

Figure 4 summarises the answers to the question "*Are you familiar with VR?*". Because VR can be interpreted in many different ways, and since we wanted to understand the exposure of respondents to VR technology, we asked which kinds of devices (if any) they had used. Based on their answers, we categorised respondents depending on their prior experience with VR solutions that are capable of full three-dimensional tracking.

Figure 5 discriminates respondents familiar with VR depending on whether they have been exposed to full 3D tracking, labelled as 6-DoF (for six degrees of freedom), in the figure's legend. We also observed a good gender balance across respondents with prior experience with 6-DoF VR (9 males against 7 females) or without such experience (11 males against 8 females).

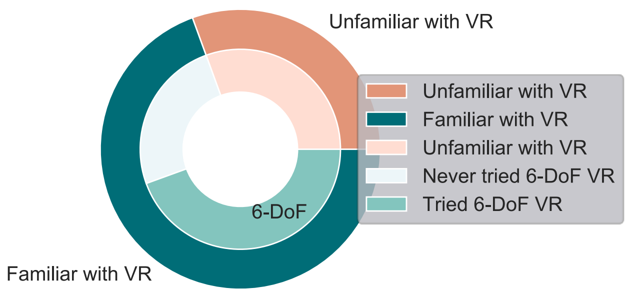


**Figure 5.** Familiarity with 6-DoF VR

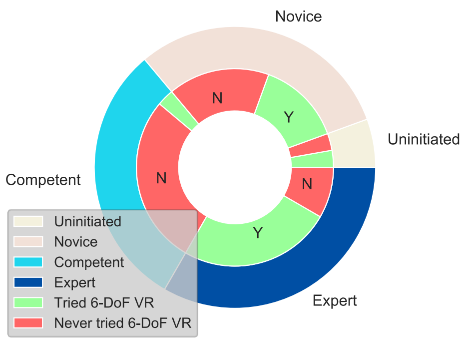


**Figure 6.** Architectural profiles compared to prior exposure to 6-DoF VR

Figure 6 follows the steps of Figure 3, putting the architectural profile in perspective with respondent's prior exposure to 6-DoF VR. We observe a VR exposure imbalance for the **Expert** and especially the **Competent** category. This imbalance should be taken into account for later analyses of our data.

We queried respondents about their frequency of exposure to VR devices. Figure 7 relates that distribution of VR usage frequency to the age and gender of respondents. With the exception of one clear outlier (at the top left), there seems to be a positive correlation between a respondent's age and his/her frequency of using VR devices. This is an interesting and perhaps unexpected observation, that contradicts the common perception that "modern technology is only for youngsters". Of course, given the limited number of survey respondents, this finding does not necessarily generalise to the entire population of architectural design practitioners.

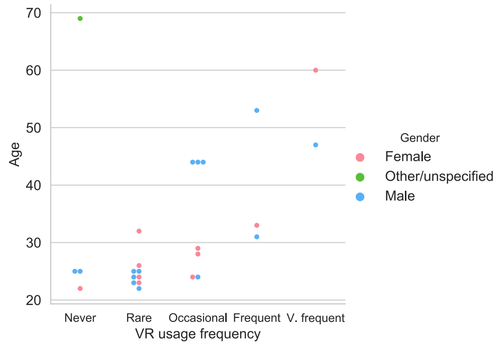


**Figure 7.** VR usage frequency and relation with age/gender

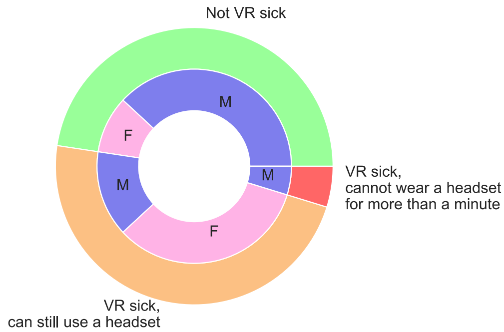


**Figure 8.** Sensitivity to VR sickness

We asked participants familiar with VR whether they have been subject to VR sickness (various symptoms generally including nausea that result from experiencing VR) and how bad they were affected by the condition. This question is relevant, as it may negatively influence one's perception on the potential of VR.

Figure 8 shows that a significant proportion of respondents (11 out of 21) experienced VR sickness, even though only one respondent indicated having been affected to such an extent that even a short exposure to VR already constituted a problem. It should however be noted that we observed a strong gender imbalance for that question (8 out of 12 male respondents indicated they did not experience VR sickness, while 7 out of 9 female respondents said they were subject to it). This finding is consistent with (LaViola Jr 2000), and can even be related to (Paillard et al. 2013) that reports women are more susceptible to motion sickness in general, even though the proportions we observe here are more pronounced than in those more specific studies.

## 3 Virtual Reality for architecture

Having discussed the profiles of survey respondents, let us dive into the core focus of our questionnaire: to assess the potential of using VR for architectural design practices. We start by exploring the current use of VR for architecture-related activities, before moving onto the future potential perceived by respondents in using VR technology.

### 3.1 Current use

For those respondents that indicated having tried VR before, we asked them via a simple yes-no question whether they had ever used the technology in the context of architecture-related activities. For those that had, we additionally queried through an open-ended question which tools they used and what limitations they encountered in using these tools. We observed that about half of the respondents had indeed used VR technology for architecture-related activities (11 out of the 21 that tried VR, with 4 that never tried VR at all).

Similar to Figure 7, we put the age of the respondents that tried VR in perspective with their answer to the question about using VR for architecture. Figure 9 presents a bee swarm plot superimposed on a box plot to convey that information. We notice that older respondents are more likely to indicate prior usage of VR for architectural purposes. Once again, it would be incautious to jump to conclusions based on that data alone.

As for the open-ended question about which VR tools were used by respondents, game engines were mentioned by a small majority of respondents (6 out of 11), with Unity3D (unity3d.com) being by far the most commonly mentioned tool (as much as 5 out of 6 responses listed this a game engine). All other tools listed in the answers were only mentioned by a single respondent and we therefore chose not to cite them here.

Only six participants answered the open-ended question about the perceived limitations of the VR tools they had experience with. Out of these comments, we noticed multiple mentions of tooling complexity (R18: "*work-intensive transition from regular CAD model to VR*"; R17: "*difficult* *to set a proper scale for the imagery*") but also user interface or interaction (R27: "*lack of easy-to-use interface*"; R56: "*limited interactions*").

Two respondents also mentioned hardware cost as an issue, while one pointed out collaboration as a challenge (R27: "*it gets kind of lonely in VR*") since his chosen solution did not allow for a multi-user experience. He adds that "*on projects with multiple stakeholders, it takes a long time to 'present', because everybody wants to 'go in'*".

VR solutions targeted at covering the needs of architects should therefore address the aforementioned limitations.

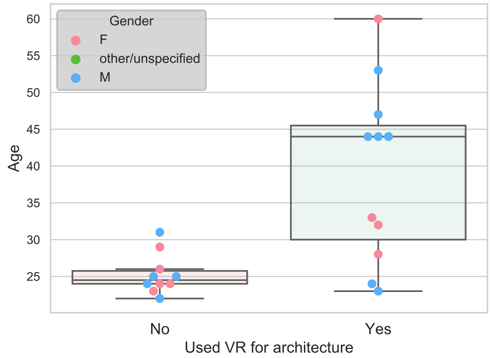


**Figure 9.** Prior usage of VR for architecture and age distribution

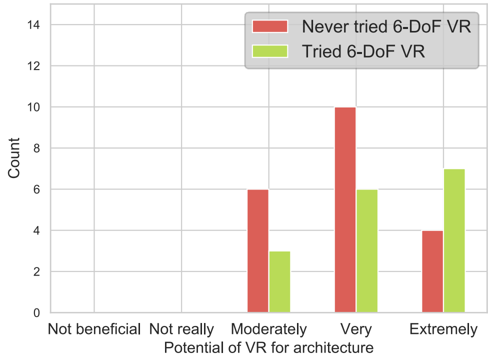


**Figure 10.** Perceived potential of VR for architecture, compared with prior 6-DoF exposure

## 3.2 Perceived potential

We asked the opinion of all respondents on the potential of using VR during architecture-related activities, regardless of their previous experience with the technology or architecture-specific tooling.

One question pertained to the perceived benefits of using VR technology as part of current and future architecture-related activities. None of the participants provided a negative answer, while as much as 75% (27 out of 36) of the respondents indicated they considered the technology is -or could be- either very or extremely beneficial for the field.

In the same vein as previous comparisons with participants' profile, we contrasted these results with the respondents' prior VR experience (Figure 10).

Apart from the general potential that respondents see in VR technology for architecture-related activities, we drilled down into the specific stages of the architectural design process that are perceived as the most suitable target for embracing VR. We proposed four possible stages in the form of a multiple-choice question: (1) after the design process; (2) during the design process, for informing stakeholders other than the designers; (3) during the design process, to be used by the designer himself; and (4) right from the start of the design process and all along.

Stage 1 covers the most common contemporary use of VR technology in the architectural context, to show a finished design to a client. Stage 2 suggests the potential to show stakeholders a work-in-progress to gather early feedback that can be taken into account for subsequent iterations. Stage 3 encompasses a workflow where the designer sporadically checks on a design in VR. Finally, Stage 4 represents the extreme case where VR is fully integrated into tools that support all steps of the architectural design process, potentially replacing non-VR solutions.

Figure 11 presents the results received for that question, compared against prior VR exposure. As expected, considering the current state of practice, a large proportion of respondents (29 out of 36) consider VR technology suitable for presenting a finished project. More surprisingly, there are equally many respondents that indicate it could be used to involve stakeholders during the design process. Slightly more than half of the respondents (19 out of 36) believe designers themselves could use the technology during their architecture-related activies, while 9 respondents indicate they believe VR tools could be used right from the start of the design process and all along.

This shows that many respondents believe in the potential of VR technology, even though Stage 4 is probably too optimistic as of now. It is hard to imagine, even with the most advanced affordable VR technology available today, how a VR-based interface could be made as effective as a desktop-based one for complex tasks that involve many options at every step (e.g., manipulating and transforming geometric shapes) as well as precise manipulation (e.g., position or size value tweaking). We note that prior exposure to 6-DoF VR experiences tends to produce a more optimistic perception of the technology's possibilities, especially for Stages 3 and 4.

### 3.3 Discussion on existing solutions for immersive architectural design

Most (it not all) major CAD tools include exporting support for the OBJ and/or FBX formats, as they are amongst the most common available options. Both formats can be used as a basis to create an immersive experience quite easily with popular game engines such as Unreal Engine or Unity3D. With the growth of the demand for VR productions, a number of CAD tools targeting architecture were developed to facilitate the creation of a VR experience, some as stand-alone software, others as plugins to existing products.

Popular examples include Twinmotion and IrisVR Prospect. These tools provide "one-click" exports from well-known modellers, such as Rhino and Revit, to a VR environment that includes the updated geometry. They therefore smooth out the burden of creating such experiences, but still provide limited control over the design artefact itself. Their live editing features are limited to superficial (external) modifications such as sun position or intensity, or texture tweaking.

Despite the relatively small population of respondents, our analysis of the responses confirms that both academics and practitioners see potential in using immersive technologies in architectural practice. It is quite clear from the answers that the technology should be integrated within the design process rather than remaining limited to showcasing finished products. There is a demand for VR tooling with model editing features (i.e., being able to modify the geometry while in VR). As for the conceptual design stage, a common example is Hyve-3D (Dorta et al. 2016), that enables design annotation and sketching through a tablet that controls a 3D cursor. The resulting sketches are then projected onto a spherical display.

Later stages of the design process have also been covered, with commercial solutions such as Gravity Sketch being available. That particular application is better suited to more precise 3D modelling, with the ability to work with additional shapes, curves and features like surface extrusion. Other commercial software, such as Mindesk also provides more advanced modelling capabilities (even more shapes, NURBS) and importantly benefits from a much better integration to existing modelling software.

The existence of the aforementioned software pieces makes it clear that several companies and research teams agree with something we identified in our surveyed population: VR also has potential for earlier stages of the design process. On the one hand, such integration is likely to help designers in visualising the architectural project they are working on. On the other hand, it is expected to benefit the clients, by making the design process more user-centric (by involving them into these earlier stages).

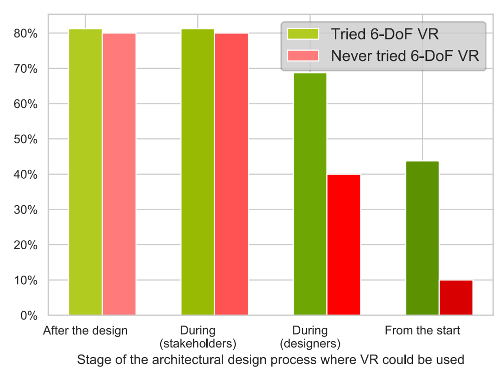


**Figure 11.** Stages of the design process suitable for VR integration

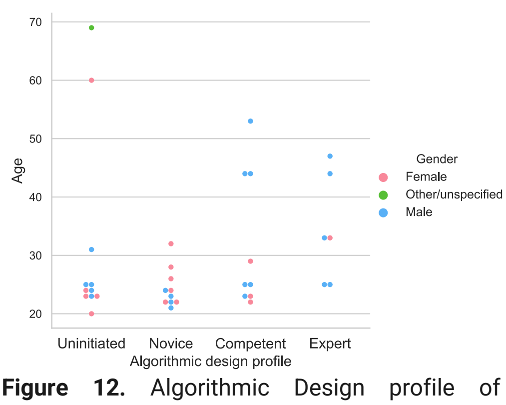


**Figure 12.** Algorithmic Design profile of the respondents

## 4 Algorithmic Design

The last part of our questionnaire focused on how VR could be used to support algorithmic design. The following section therefore talks about the answers we received on the subject.

### 4.1 Definition of Algorithmic Design

*Algorithmic Design* (AD) is an architectural design paradigm that involves generating geometries using algorithms that are often driven by parameters that can be changed, allowing designers to explore different solutions by tweaking the values of these parameters. Algorithms can be represented in textual or visual forms, sometimes interchangeably, and may correspond to different programming paradigms.

In architectural practice, the most common form is flow-based programming (Morrison 1994) through a visual representation, with tools like Grasshopper, GenerativeComponents and Dynamo Studio, standing out as the most popular software solutions. The final geometrical output is constructed by connecting processes that have an internal behaviour and return an output value (e.g., an intermediary geometry). Figure 13 shows such a visual program to construct a parametric cube, together with the geometry it generates.

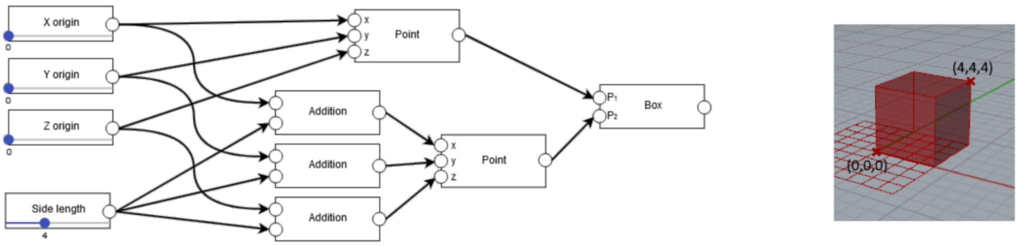


**Figure 13.** Algorithmic Design model (left) for a cube, with a visualisation of the geometry it generates (right)

AD is often referred to as *computational design* or *parametric modelling* (Caetano et al. 2020). Both of these terms appear too generic since they could apply to non-algorithmic design as well: the former simply informs that a computer was used, while the latter signals that the design is driven by parameters; parametric modelling (or parametric design) is in fact regularly confused with Building Information Modelling (BIM). Despite that flaw, the “parametric modelling” term is quite common amongst practitioners, and we therefore had to include it in the survey questions in case the respondent was not familiar with the AD appellation.

### 4.2 Demographics of respondents

For this part of the survey on VR for AD, we only considered respondents that indicated they were aware of algorithmic design or parametric modelling tools. The vast majority (34 out of 36) signalled an awareness of such tools. Given the vague and confusing term "parametric", and in order to better appreciate the level of understanding of what the paradigm entails, we asked respondents “*How would you define parametric modelling/design?*”.

In a similar way to (Stals et al. 2018), we classified respondents based on their answer into three distinct categories: “wrong definition”, “correct definition”, and "unclear definition". The latter category contains respondents that mentioned the parametric aspect but whose proposed definition did not contain any reference to algorithms, programming or interlinked components, and did not mention that variations of parameter values produce chain reactions. Such a definition therefore also applies to non-AD software since all you need is the presence of parametric objects to fill the bill (e.g., parametrised primitive shapes in traditional CAD software).

Out of 34 respondents for that part of the questionnaire, only 12 gave a definition that we consider to be correct, with 18 persons providing an answer we classified as unclear.

By combining that information with the respondents’ architectural profile, we defined the AD profile consisting of four categories: **Uninitiated**, **Novice**, **Competent** and **Expert**. Figure 12 shows the distribution of these classes across respondents, compared with their age.

We also asked the 29 respondents that indicated having practical experience with AD software to list the tools they were working with. All but one respondent (28 out of 29) mentioned Grasshopper, and two of them additionally mentioned Dynamo.

## 4.3 Virtual Reality for Algorithmic Design

We queried respondents on the integration of AD software and VR hardware. At the beginning of the corresponding section of the questionnaire, we asked each respondent to look at an online video (youtu.be/uEXiCbdJHRY) demonstrating a proof-of-concept application that allows Grasshopper users to modify a model within an immersive environment (Coppens et al. 2019). The proposed prototype demonstrates the feasibility of editing a Grasshopper model in VR, as well as the ability to provide a user interface adapted to that type of environment.

After viewing the video, each respondent was presented with a question on the usefulness of such VR-enabled functionality if it were combined with a 3D visualisation of the geometry being worked on. The answers for that question reveal a mixed reception, with slightly over half of all respondents (18 out of 34) considering VR functionality as "probably not useful" or "not useful".

Since we realise that experiencing VR is quite different from watching a video about it on a traditional 2D screen, we explored the relation between these answers and the earlier responses linked to prior exposure to VR technology.

Figures 14 and 15 present bar plots that depict the answers on usefulness compared respectively against prior exposure to 6-DoF VR and prior usage of VR for architecture-related activities. Note that the latter only takes 20 answers into account, since we did not include respondents that indicated they were not familiar with VR or had never experienced the technology (Figure 14 does take them into account).

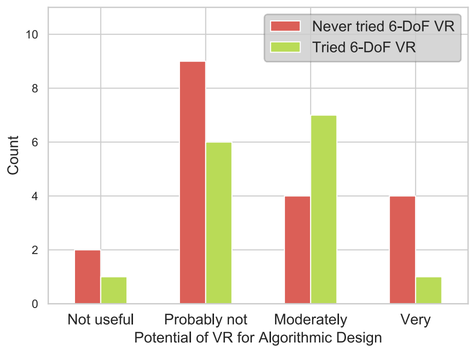


**Figure 14.** Usefulness of VR for Algorithmic Design, compared with prior exposure to 6-DoF VR

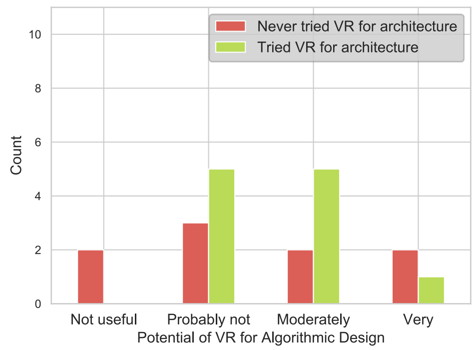


**Figure 15.** Usefulness of VR for Algorithmic Design, compared with prior exposure with VR for architecture

It seems that the proposed prototype was slightly better received amongst respondents with prior exposure to 6-DoF VR and VR tools for architecture, respectively with 54.5% (6 out of 11) and 53.3% (8 out of 15) of the answers that consider it to be at least "moderately useful" within these subgroups of our population, although the difference is not statistically significant.

Then, respondents were asked about opportunities they see for VR in the context of AD. We received 16 responses, 9 of which mentioned the necessity to add a live preview of the geometry in the background, with R17 stating that a VR visualisation would help "*detect issues easily*" and R18 suggesting to "*assess the implications of parametric model variations*".

With regards to interaction with such a system, we received three mentions of the dimensionality mismatch between the 3D environment and an inherently-2D visual programming language, which is hardly avoidable if we want to preserve a bidirectional link with the desktop-based software (i.e., being able to work in the desktop version of Grasshopper with a model modified from the VR interface).

Five respondents (31.2%) indicated they would be more interested in "physically" or "directly" modifying the geometry. Although this seems strongly related to a more traditional direct modelling (i.e., outside of AD) approach, it would be possible to provide such a feature for some specific Grasshopper components. Typically, that would be doable for components and parameters clearly mapped to a 3D-located geometry or effect (e.g., to specify a point's position or to control extrusion parameters) but is not applicable to AD as a whole.

### 4.4 Discussion on existing solutions for immersive Algorithmic Design

These results show that there is some level of interest for applying VR in the context of AD in particular. While some of the solutions described in Section 3.3 allow AD users to create VR visualisations easily, there are options worth mentioning for VR-based editing of AD models.

A first level of interaction would be parameter adjustment i.e. a VR user changes parameter values from a VR application that also includes a 3D visualisation of the generated geometry.

Two independent yet similar prototypes (Hawton et al. 2018) and (Coppens et al. 2018) to enable such interaction with Grasshopper models were presented in 2018. The former worked with the Oculus Rift headset, while the latter used the first generation of the HTC Vive headset. Since both prototypes rely on cross-platform toolkits, they would likely work on all major VR head-mounted displays with minimal (if at all) adjustments.

In both cases, the user is presented with a panel, attached to a standard VR controller (tracked in 3D), that contains a list of parameters whose value can be changed. They both support number values, tweaked through the manipulation of sliders, and (Coppens et al. 2018) also allows for Boolean values to be altered through virtual toggle switches. Changes made to the model's value are sent back to Grasshopper so as to modify the generated geometry whose updated version is, in turn, fed back into the VR environment.

While previously mentioned solutions allow designers to tweak parameters, they cannot be used to add or remove components, nor do they allow to edit links between these components.

To overcome that limitation, researchers have started working on adding control over the model itself. An example from the recent literature (Castelo-Branco et al. 2020) relies on desktop-mirroring i.e. the VR user has access to a "window" that mirrors the view of the computer running Grasshopper. In order to interact with that window, the VR controllers "simulate" a standard desktop mouse, with a "point and click" approach.

The Mindesk commercial software product was updated to provide the same functionality, using the same approach of mirroring the computer screen.

Providing a mirror view of the desktop interface coupled with simulated mouse and keyboard input means that the user gets access to the same feature set as with the desktop tool itself. Nevertheless, interacting that way is not as efficient as doing so from the original tool, and it does not take full advantage of the 3D-tracked controllers either.

Improving the user experience and embracing more appropriate interactions for visual programming in a VR environment are challenging tasks. As mentioned earlier, our questionnaire included a video to present a prototype we developed (Coppens et al. 2019) that enables VR users to modify a Grasshopper model with a VR-specific interface. We indeed proposed a VR visualisation that essentially creates 3D versions of Grasshopper components, and places them on a virtual table. We explored some 3D interaction techniques (based on the grasping and the pointing metaphors) and devices (standard VR controllers and a hand-tracking sensor), and these interactions are also included in the video.

Based on the answers to the survey, in order for a VR-based system to be deemed useful for visual programming, the interactions and integrations with existing systems need to be pushed further. This reinforces our conviction that more work is needed in that specific domain, especially with regards to interaction modalities and adapted user interfaces. It should however be noted that, based on the feedback we received, parameter tweaking for AD models may be enough for most users relying on the paradigm.

## 5 Threats to validity

The most obvious threat we face with this survey is the population size. Answers from 36 respondents provide a good start to notice patterns but are not sufficient to claim that our conclusions are representative of the entire population of architects. It also hinders our ability to test statistical hypothesis on the surveyed population, since it is not possible to obtain sufficient statistical significance with such a small population size.

We also have to consider a potential selection bias, since a large majority of the respondents familiar with AD are Grasshopper users, because some of the venues we selected to distribute the questionnaire are biased towards that particular software. Unfortunately, we could not avoid this selection bias because the AD part of our questionnaire starts with the presentation of a prototype that has been developed for that tool, specifically. We also observed that a significant part of our respondents were students, with a rather academic (as opposed to a professional) population in general. We should also keep in mind that a questionnaire with "VR" in its title may be more attractive to VR enthusiasts. As for the effect of gender on the answers, no significant difference was found and gender balance was mostly observed.

Regarding the questionnaire itself, we showed an incomplete prototype through a video at the start of the AD section, so the respondent can only project himself and try to imagine what a full-fledged complete VR experience would be like. This might have influenced the respondent's perception of what is possible with the technology.

Finally, we face a self-reporting bias for the question on VR sickness, since users may have different tolerance levels before considering that something is bothering them. We were exposed to the same threat for the questions about the VR, architectural or AD profiles, but we mitigated it by asking multiple questions to better evaluate the expertise or exposure level.

## 6 Conclusion

Through this survey and its results, we aimed to identify the needs of architectural practitioners with regards to VR integration in their field. Our initial assumption that the technology should be used earlier in the design process matches respondents' opinion, with a clear demand for a more user-centric approach to involve stakeholders during the design process. VR technology should be integrated further into design practices and go beyond the current usage. It should enable architects to model, transform and evaluate different configurations.

The feedback we obtained on our suggested prototype for AD in VR shows that more work is needed in terms of user interaction and interfaces, but there is definitely a demand for immersive tools that would enable at least parameter adjustments to be made in architectural designs.

By sharing these findings, we aim to help research and development teams that work on integrating VR solutions in the context of the architectural design process to position their future work so as to fulfil the needs our analysis of the survey results identified.

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