Design Science

Investigating VR sketching in automotive concept design: advancing spatial, environmental and operational fidelity

Charlie Ranscombe[1], Keun Lee[2] and Jo Kuys[3]

[1]*ARC Centre for Next-Gen Architectural Manufacturing, Department of Architectural and Industrial Design, Swinburne University of Technology, VIC, Australia*
[2]*Department of Industrial Design, College of Fine Arts, Hongik University, Seoul, Republic of Korea*
[3]*Department of Architectural and Industrial Design, Swinburne University of Technology, VIC, Australia*

Abstract

VR sketching tools have matured to a practical level, enabling use across various 3D design disciplines. Studies into VR sketching in design report beneficial affordances but are based on brief testing of tools in simulated tasks. Consequently, there is a knowledge deficit in understanding how to effectively integrate VR sketching into design projects. We address this gap with a case study on the sustained use of VR sketching in 10 automotive concept design projects over 10 months. In analysing designers' logbooks, which captured design development, and post-study reflections, we show how the affordances of VR sketching outlined in literature manifest in practice. Specifically, we show how and when designers can exploit the precedence of 3D geometry embodied in VR sketches to advance the design process in terms of several dimensions of design fidelity. We highlight where process advantages are realised through (1) increased spatial fidelity, reducing the time required to iterate 2D sketches, (2) operational fidelity supporting dynamic testing of concept functionality via animation and (3) environmental fidelity supporting contextualising components and storytelling. As such, our findings highlight how and when practitioners can realise the comparative benefits of VR sketching alongside traditional sketching and 3d modelling during the concept design process.

Keywords: Affordance, Conceptual design, Design tools, Design practice, Virtual reality

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Corresponding author
Charlie Ranscombe
cranscombe@swin.edu.au

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1. Introduction

Digital technologies can transform product development, providing designers with powerful tools to both enhance creativity and process efficiency. Virtual Reality (abbreviated to VR from here on in) is an example of such a technology that has become well-established within design processes. Its established use is in the immersive visualisation of concepts at 1:1 scale (Bourdot *et al.* 2010; Camburn *et al.* 2017; Horvat *et al.* 2019; Lee, Yang, & Sun 2021; Oti & Crilly 2021; Harlan, Goetz, & Wartzack 2025), which can assist in conceptualising products to verify qualities of the design (de Klerk *et al.* 2019; Horvat *et al.* 2019; Howell *et al.* 2024), helping to advance designs with reduced investment in physical prototypes (Kent *et al.* 2021; Harlan *et al.* 2025).

VR sketching platforms are comparatively newly available technology for designers. Although VR sketching has had a presence in literature since the mid-90s (Deering 1995), it has only relatively recently been integrated in commercial automotive design practices (Leaver 2020) via bespoke software developed for the manufacturer (BrainXchange 2020). The arrival and evolution of "off-the-shelf" VR packages since circa 2017 established the tool as now available and viable for the design community to adopt. The value proposition for using VR sketching can be summarised as the affordances of sketching integrated with immersive VR (see Section 2.2 for detailed discussion of affordances). Sketching is consistently regarded as an essential tool to externalise and share design ideas (Cross 1982). In particular, its fast and flexible capacity to depict ideas at low fidelity is highlighted as a key positive affordance (Goldschmidt 1991). In comparison, CAD is highlighted as having affordances more suited to later phases (capacity for higher design fidelity) at the cost of slower, more involved interaction, making it less suited for the early stages of the design process (Robertson & Radcliffe 2009). Thus, the value of VR sketching lies in affordances for speed and low fidelity combined with advanced immersive visualisation capability (akin to CAD and 3D modelling), which together can advance the project through the design process faster with less investment in expensive 3D modelling and prototyping (Jin & Lee 2019; Kent *et al.* 2021; Oti & Crilly 2021).

While these works underscore the affordances of VR sketching that compel its use in contemporary industrial design processes, to date, there exists little in the literature to explore how VR sketching should be implemented within concept development processes. Moreover, the majority of studies into VR sketching test the platforms in controlled settings via short design tasks (see Section 2.2). As such, they lack insights on sustained use of the technology throughout the substantially longer duration of typical design projects. It follows that there is a lack of understanding of the integration of VR sketching within concept design processes and alongside existing tools (3D modelling and physical prototyping), and thus guidance on best practices to realise the advantages highlighted by short-term studies. As such, this article presents research with the aim of understanding how affordances of VR sketching manifest in the concept design processes, and thus, the guide more widespread integration within design practice.

We seek to meet this aim by posing and answering the following research questions:

- RQ1. Which affordances of VR sketching are observed in practice and in which design process phase?
- RQ2. How do the affordances observed in practice lead to process efficiencies in terms of resources or project duration?
- RQ3. How does a VR sketching concept design process model compare with a traditional concept design process model?

The article proceeds as follows: Section 2 outlines key background literature. The rationalisation of case studies research methods is given in Section 3. Results are presented in Section 4 and discussed in Section 5 with conclusions drawn in Section 6.

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2. Background

This section outlines the automotive concept design process, the context of case studies reported later in the article and signposting process phases in which VR sketching is integrated. It then surveys the literature on immersive design tools to outline the key affordances to be investigated in case studies. This also illustrates the gap in the literature, a lack of longer-term studies into sustained use and thus knowledge on the practical integration of VR sketching.

2.1. Automotive concept design process

Concept cars are visionary prototypes looking 5–20 years into the future, pushing the boundaries of automotive design, technology and functionality (Hirz *et al.* 2013). Unlike the traditional automotive design process, where the primary focus is on technical production considerations, the concept car design process places a strong emphasis on concept development and showcasing the future design directions of automakers (Lu & Lu 2012). From market research to final conceptualisation, designers progress ideas beginning with rough ideas in low fidelity that progress to marker rendering and digital sketching before advancing to (digital) 3D modelling for surface comprehension and clay modelling (Tovey, Porter, & Newman 2003; Ranscombe 2012; Hirz *et al.* 2013; Galiè *et al.* 2024). While this process is similar to the traditional automotive design approach, the notable deviation is in its forward thinking focus on future concepts that are more akin to the generalised steps in the development of consumer products in new product development.

The process begins with thorough market research and trend analysis to identify emerging technologies, discern consumer preferences and recognise prevailing design trends. The first design phase, (1) Initial Ideation, comprises considerable time engaging in sketching exercises with pen and markers, generating a multitude of ideas in low fidelity (Tovey *et al.* 2003; Galiè *et al.* 2024). Ideas for both exterior and interior design are matured through sketches with increasing fidelity to reach a point where preferred ideas are selected based on alignment with envisioned design directions for development in the next phase (Rodgers, Green, & Mcgown 2000). The next phase (2), Key Line, focuses on refining vehicle silhouette, stance, key lines and daylight opening position at a 1:1 scale via side, front and rear profiles (Ranscombe *et al.* 2012; Galiè *et al.* 2024). These are developed iteratively, creating drawings at a 1:1 scale but supplemented with multiple perspective sketches and renderings (Donnici *et al.* 2020). Once profiles are verified, the process continues to the third phase (3) Ergonomic Study. The activities in this phase are similar to the Key Line phase (1:1 scale drawings supplemented with perspective sketches); however, the intent is to iteratively develop and refine ergonomic considerations and integrate both interior and exterior considerations. As ergonomics are defined, the design undergoes Concept Development (4), where style and functionality are refined using sketches but also integrating 3D Modelling (CAD). This phase allows designers to explore and validate the feasibility of their concepts with increasing fidelity, refining further user functions and experience alongside surface details, and considering different materials (colour and trim). Once the overall concept is developed in suitable fidelity, the process proceeds to the (5) Clay Modelling. Here, 1:1 scale clay models are generated to better understand and make nuanced edits to

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surfaces and further test interaction between the user and the vehicle. The final phase is (6) Presentation, where storyboarded narratives and user interactions are simulated (Rodda *et al.* 2022) often using CAD and animation software, creating hyper-realistic (high fidelity) renderings of the design. The goal of the presentation is to introduce wider company stakeholders to the new concept car design to ascertain whether the concept (or elements of the concept) could advance for further development. As with the typical product development process, we see a succession of phases followed to develop the design fidelity, verifying aspects of the design to build confidence to proceed to the subsequent phase. Corresponding tools were used to transition from rough sketches (very low fidelity) to more detailed sketches, then 3D modelling (CAD), prototyping resulting in hyper realistic (high fidelity) presentation of the concept.

2.2. Affordances of VR sketching

This section surveys extant literature to outline our understanding of the affordances of VR visualisation and VR sketching that drive its usefulness in the design process. VR environments provide an immersive and holistic view of the design, as such offering the enhanced ability to visualise the design at multiple scales but most importantly at 1:1 or "real life" scale (Bourdot *et al.* 2010; Horvat *et al.* 2019; Lee *et al.* 2021; Oti & Crilly 2021). Furthermore, the immersive quality means that by navigating the space it is possible to visualise the design from a multitude of viewpoints (Rahimian & Ibrahim 2011; Wodehouse, Loudon, & Urquhart 2020), enhancing the capacity for designers to understand and evaluate the design (de Klerk *et al.* 2019; Horvat *et al.* 2019; Wodehouse *et al.* 2020; Maurya, Mougenot, & Takeda 2021). Researchers also note how visualisation becomes closer to experiencing the design via presence within the virtual environment (Lee, Yang, & Sun 2019; Zhang *et al.* 2020), which can include environmental and contextual elements simulating how and where the product would be used (Kent *et al.* 2021; Ranscombe *et al.* 2023). As such, VR visualisation can support improved estimation of scale to "experience" spaces immersively but also the capacity to test the usability of key qualities (de Klerk *et al.* 2019; Horvat *et al.* 2019; Lee *et al.* 2019; Zhang *et al.* 2020; Maurya *et al.* 2021). Furthermore, the immersive experience can occur concurrently with multiple stakeholders potentially in distributed locations, including non-designers, who also benefit from a heightened capacity to evaluate (de Klerk *et al.* 2019). Concerning benefits for the design process, the above ability to visualise, experience and evaluate designs in virtual states saves in terms of prototyping costs and overcoming practical and budgetary constraints in producing physical representations (Kent *et al.* 2021; Ranscombe *et al.* 2023; Zhang *et al.* 2023).

The recent advent of sketching environments within VR leverages the above benefits of visualisation and evaluation within an immersive "creating" environment rather than simply an evaluative environment. Sketching is viewed as a fast low-fidelity approach to visualisation. Hence VR sketching when used in the early phases of a design process presents an opportunity to bring the aforementioned advantages in visualisation to an earlier phase of the process where fast flexible sketch expressions of ideas are optimal (Jin & Lee 2019; Oti & Crilly 2021). Instead of needing to invest in digital models that are the basis for VR evaluation, designers have the opportunity to quickly sketch the emerging design

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in 3D, which further compounds the advantages of cost saving (Kent *et al.* 2021; Zhang *et al.* 2023). When compared with the use of traditional analogue sketching, VR sketching presents an opportunity to reduce the need for repeated creation of different views/sketches (Yang & Lee 2020). In turn, this facilitates faster iteration of designs as compared with CAD modelling and the VR evaluation paradigm (Rahimian & Ibrahim 2011; de Klerk *et al.* 2019; Jin & Lee 2019; Yang & Lee 2020) based on the speed with which a 3D sketch is created versus a 3D model coupled with an immediacy between design action/iteration and feedback (Jin & Lee 2019). Ultimately further improving the design process in terms of greater cost savings and efficiency via greater iteration in earlier phases (Milella 2015; Kent *et al.* 2021; Ranscombe *et al.* 2023). A summary of the affordances described in this section is included in Table 2.

Despite the established use of VR for visualisation and the compelling prospect of VR sketching, widespread adoption is limited. An obvious barrier relates to training. Many designers and design firms acknowledge the potential benefits but see the requirement to invest significant time in training as difficult to reconcile against the limited understanding of how it can feature within their design process (de Klerk *et al.* 2019; Yang & Lee 2020; Lorusso *et al.* 2021). Part of this issue is acknowledged as relating to the challenges of learning a new user interface and user experience (Jin & Lee 2019; Maurya *et al.* 2021; Oti & Crilly 2021; Zou *et al.* 2023). Zhang *et al.* (2023) highlight the issue of training is further compounded by designers' not having a clear expectation of its use. This can be viewed as designers not knowing how the tool and output can integrate within the design process in terms of the fidelity created and the audience. For example, it is not yet established the extent that low-fidelity visualisation can offer the necessary precision to make design decisions, or indeed the nature of those decisions in terms of typical decision-making milestones. Coincidentally, Oti & Crilly (2021) highlight how, while the tool presents many advantages via offering complementary affordances, designers must still use established tools at certain points. This potentially explains the uncertainty around workflow integration and thus hesitance. A final limitation in our understanding of implementing VR sketching is the question of logistically how the results of VR sketching can be compatible with existing digital tools (de Klerk *et al.* 2019; Laing & Apperley 2020; Zhang *et al.* 2023).

Acknowledging the above challenges to immersive technology adoption in design, Cox, Hicks, & Gopsill 2022 seek to further investigate dimensions of fidelity as a basis to understand and provide best practices. This is significant to our study for two reasons. First, their intent aligns with that of this article in terms of exploring best practices with emerging design technologies. Second, the taxonomy of fidelity presents a valuable tool to more deeply reflect design fidelity manifesting in design artefacts. Specific dimensions of fidelity are described in greater detail in Section 3.6 as a basis for examining design visualisations.

In conclusion, this section highlights key affordances of VR sketching to enhance visualisation, evaluation and iteration within the design process through immersive but relatively low-fidelity representations. However, the integration of VR sketching remains hindered by uncertainty on how it should be best integrated into the design process. This further underscores a gap in the literature (long-term study of the sustained use of VR sketching) which our study seeks to address.

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3. Method

This section begins with a rationalisation for a qualitative research method, followed by a description of the case studies, participants and the approach to data collection and analysis.

3.1. Rationalising a qualitative approach

As previously stated, the research aims to understand how the affordances of VR 3D sketching manifest in practice. It follows that a qualitative longitudinal approach is essential to capture insights on the application of VR sketching over an entire project process. This approach ensures we can track the subtleties of integration during different phases of the concept design process and reflects the real-world challenges and benefits that designers encounter over a period of months interacting with the tool alongside traditional design tools. For these reasons, our approach is distinct from the methods adopted in extant literature using experimental approaches. Specifically, extant studies use short design tasks (up to 3 hours) under observation (Rahimian & Ibrahim 2011; Lee *et al.* 2019; Yang & Lee 2020; Lee *et al.* 2021). Or, controlled comparative experiments designed to test a specific utility or affordance where participants interact with VR sketching for up to 90 mins (de Klerk *et al.* 2019; Horvat *et al.* 2019; Jin & Lee 2019; Maurya *et al.* 2021; Oti & Crilly 2021; Zou *et al.* 2023). While we acknowledge these studies have value in empirically establishing positive affordances of VR sketching, they do not have the scope to offer insights on its sustained application over entire design projects, which is essential to develop a complete understanding of how experimental research relates to design practice (Lauff 2018; Crilly & Moroşanu Firth 2019). Thus, we argue a long-term qualitative approach is ideally suited to address the research aim of understanding how affordances of VR sketching manifest in practice, and thus extend our understanding beyond extant literature.

3.2. Case studies

Our case studies comprise 10 projects undertaken by final-year automotive design students from the author's institution in collaboration with practising designers from Hyundai Kia Motors and Klio Design. Each project is undertaken over 10 months between May 2021 to February 2022 comprising the typical phases and tools of the automotive concept generation process outlined in Section 2.1. All projects had the same overarching brief; "*develop a future mobility concept.*" Yet, the approaches and resulting designs produced in each project are diverse reflecting the different (approaches) of students. Descriptions of each project alongside their sponsoring organisation are listed in Table 1. Student projects are used as access to practising designers' work over the extent of the project duration is not feasible due to IP concerns and the extent to which professional designers were able to dedicate time to the study. Instead, to ensure that projects and processes remained grounded in industry practices, professional designers assumed the role of "design manager." In this role, the professionals were responsible for reviewing and giving feedback on work and advising on progression through the design process to achieve the best possible design outcome.

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Table 1. Description of project topics and associated industry sponsor

Project number	Industry sponsors	Project Description
1	KIA	Purpose Built Vehicle (PBV) as a sustainable mobility solution.
2	KIA	Agricultural working vehicle with 360 degrees rotating main body for better workflow.
3	Hyundai	Multifunctional vehicle concept with exterior sitting profile.
4	Hyundai	Off-road future vehicle concept with airlift function.
5	Hyundai	Autonomous vehicle with moving living space for the future.
6	Hyundai	Future mobility solution for a ride-share concept.
7	Hyundai	Multifunctional logistic delivery vehicle concept.
8	KIA	Sports ride vehicle concept with new riding ergonomic study.
9	Hyundai	Sedan converted camping vehicle concept.
10	Hyundai	Flexible future mobility ride-share with modular concept.

3.3 Participants

Ten final-year automotive design students (4 female and 6 male) aged between 22–25 years worked on their sponsored projects alongside three Automotive designers, one from Hyundai Kia Motors and two from Klio Design. This sample of final-year students have 3 years of design experience and thus are deemed adequately equipped in terms of design skills and knowledge of the design process to offer insights on the practical application of VR sketching. Figure 1 includes sketches indicative of the sketching skill level of participants. Furthermore, the guidance offered by industry project partners ensures the designers (although only junior designers early in their careers) have access to the requisite knowledge and support to work through the project in a manner akin to professional practice.

3.4. VR sketching training

In the first week of the Initial Ideation phase of the project case study, all student designers underwent training in the VR sketching software "Feather" adopted for

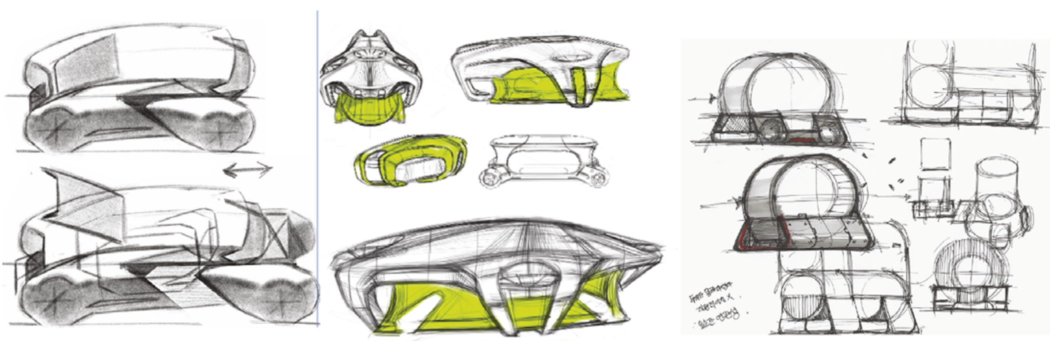

Figure 1. Sketches indicating participants' skill level with traditional sketching.

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the duration of the study. This training comprised a series of exercises to bring student designers to a skill level (threshold skill) to competently and independently use the tool within their projects (Lawson 2002; Ranscombe *et al.* 2023). Furthermore, training was essential for participants to understand the relative strengths of VR sketching compared with existing tools (traditional sketching and CAD modelling). From a methodological perspective, training was also important to provide a degree of control for the skill level across the sample of participants.

3.5. Data collection and instruments

The primary data sources are logbooks completed by students which are triangulated with post-study reflections by designers at the conclusion of the project.

3.5.1. Logbooks

Design logbooks comprise developmental work that chart the evolution of the design. This is typical of design industries to track progress and report. The content is primarily visual, comprising representations of the design in different states as it evolves in fidelity from preliminary sketches during initial ideation (phase 1), through key-line development (phase 2), ergonomic studies (phase 3) and concept development (phase 4), through to modelling (phase 5) and final presentation (phase 6). As such, it presents an opportunity to investigate how the use of VR sketching manifests in the design representations at each of these stages.

From a methodological perspective, the choice to analyse logbooks is rationalised as presenting a feasible and sustainable means to capture the process over the full duration of an extended design process without disrupting the natural design activity (Jonson 2005; McAlpine *et al.* 2006; Cash *et al.* 2015). Our use of logbooks follows research precedents in project-based design and engineering research highlighting their validity in capturing design artefacts (Jonson 2005; Pedgley 2007), design processes, insights and decisions made (McAlpine *et al.* 2006; McAlpine, Cash, & Hicks 2017) and to reflect critically on the process (Sadokierski 2020). In our study, the logbooks are in the form of digital design folios where students record ideas, design developments, key milestone presentation content, decisions made and reflections on using VR sketching within their design process. Being digital artefacts, they also include short videos/ and animations.

3.5.2. Post-project reflection and survey

The secondary data collection is in the form of structured reflections and a short survey to capture summative views on the use of VR sketching in their projects. Designers responded to prompts on (1) key advantages, (2) challenges or difficulties and (3) recommendations for improving the tool. Reflections were recorded and transcribed for analysis (see Section 3.6). The accompanying survey was devised to capture ratings on the extent key affordances were realised during the project. The following questions were posed concerning the typical design process and then repeated concerning the VR sketching design process. Questions 1–3 are devised based on key literature on the objectives of visualising concepts Speed and accuracy, and presentation usability (Oti & Crilly 2021; Kuys, Ranscombe, & Zhang 2023). Questions 4 and 5 are devised from the literature on barriers to

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adoption, convenience and compatibility (de Klerk *et al.* 2019; Laing & Apperley 2020; Zhang *et al.* 2023).

1. On a scale of 1–10 rate your speed of sketching designs (10 extremely fast, 1 extremely slow).
2. On a scale of 1–10 rate the accuracy of your sketching (10 extremely accurate, 1 extremely inaccurate).
3. On a scale of 1–10 rate the usability of sketched designs for presentation purposes (10 extremely useable, extremely unusable).
4. On a scale of 1–10 rate how convenient you find sketching tools/process (10 extremely convenient, extremely inconvenient).
5. On a scale of 1–10 rate the compatibility of sketching tools/process with the other tools you use when designing concepts (10 extremely compatible, extremely incompatible).

3.6. Analysis

Both data sets are analysed following the same overall approach to thematic analysis. First identifying evidence of (logbooks) and or indications of (reflections) key affordances highlighted in the literature. This provides an overview of which affordances are realised in practice over the duration of the project and at which phase. Second, data are analysed to explain how the affordances manifest in the designers' project practice. In the case of logbooks, this means identifying design work that exemplifies or demonstrates an affordance, which is then confirmed/further reflected on during interviews (addressing RQ1). Manifestation of affordances is then framed in terms of design fidelity following the convention of Codner & Lauff (2024) using the characterisation of types of fidelity presented in Cox *et al.* (2022) in order to draw comparisons between the use of VR sketching and traditional tools. Manifestation of affordances and framing in terms of fidelity are used together to outline specific design process verification that is achieved and thus design process advantages (addressing RQ2 and RQ3).

3.6.1. Coding scheme

The coding scheme devised for logbooks/diaries and post-project reflections is now presented. Affordances are grouped by categories set out in the systematic review by Kent *et al.* (2021). It begins with a deductive coding phase where coders identify references to, or evidence of, the key affordances highlighted in the literature. Where affordances are identified, the design phase in which they occur is recorded. A further inductive phase is added, whereby the coder sought to identify themes emerging from data on how positive affordances of VR sketching manifest in design practice. The approach to coding is primarily visual content analysis (Brown & Tiggemann 2016; Kuys *et al.* 2023) but also includes verbal coding of notes. Table 2 outlines the coding scheme to identify affordances. The definitions of the six design phases described in Section 2.1 are used to define and identify the respective phase in which affordances are identified. Figure 2 illustrates the two-step deductive and inductive coding process applied to logbooks. The coding scheme was validated by pretesting by coders coding independently and checking alignment. Coding was conducted by academic researchers who were not involved in teaching or supervising the project. This approach ensured that coders possessed

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Table 2. Coding scheme used to analyse logbooks and reflections. Note only codes 1–8 are used when analysing logbooks. Codes 1–12 are used when analysing reflections

No.	Code	Definition
	Visualisation	
1	Holistic view	References or demonstrates a holistic or comprehensive 3D depiction of the idea or design
2	Multiple viewpoints	References or demonstrates the ability to review the idea or design from multiple viewpoints either by a single user or multiple users concurrently
3	Contextualising	References or demonstrates visualising designs within a real-world context (AR) or digital environment within an immersive space
	Creation and configuration	
4	Creation with dimensional understanding	References or demonstrates a capacity to perceive at-scale dimensional considerations while sketching in the VR space
5	Immediacy	References or demonstrates the immediacy with which edits to a design can be immediately/rapidly perceived by users within the VR environment
	Integrated analysis	
6	Testing	References or demonstrates the capacity to test usability or human factors at low fidelity resulting from immersion within the 1:1 scale VR environment
	Collaboration	
7	Improved communication and understanding	References or demonstrates a heightened ability to communicate considerations of scale and usability/human factors with the design manager or audience during presentation.
8	Concurrent review and feedback by distributed teams	References or demonstrates the capacity to review and seek feedback from users in the same immersive environment but in different geographic locations.
	Barriers and issues	
9	Precision	Negative sentiment in reference to uncertainty on the extent the VR sketch representation was able to resolve issues or progress the design or meet milestone
10	Training	Negative sentiment in reference to a level of training or competence required to reach design intent
11	User interface	Negative sentiment in reference to any UI qualities of the VR sketch environment
12	Compatibility	Negative sentiment in reference to the compatibility of VR sketching software and assets with other software or phases of the design process

the necessary background knowledge while reducing potential biases associated with direct participant interaction. The survey is analysed via descriptive statistics to provide a holistic view of the strengths of VR sketching. Namely the mean average rating of the performance criteria addressed in the survey.

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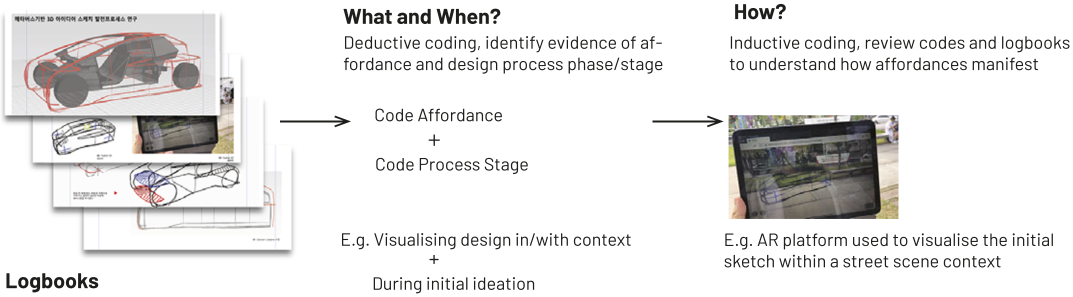

Figure 2. Illustration of the process for coding logbooks.

4. Results

4.1. Logbooks

Table 3 presents the number of projects in which codes are identified, and cross-referenced with the phase in which they occurred. For example, we saw evidence of the affordance "Holistic View" during the "Initial Ideation" phase in 9/10 projects, whereas we only saw evidence of this affordance during the "Key Line" phase

Table 3. Frequency of affordances and corresponding design phase identified across all logbooks

No.	Code	Process phases						
		Initial ideation	Key Line	Erg. Study	Concept Dev.	3D modelling	Clay modelling	Presentation
	Visualisation							
1	Holistic view	9	2	0	0	0	0	0
2	Multiple viewpoints	10	6	1	0	0	0	1
3	Contextualising	7	1	3	2	1	0	2
	Creation and configuration							
4	Creation with Dimensional understanding	10	8	9	1	0	0	0
5	Immediacy	2	4	4	0	0	0	0
	Integrated analysis							
6	Testing	3	3	6	6	3	0	2
	Collaboration							
7	Improved Communication and understanding	0	0	0	2	1	0	5
8	Concurrent review and Feedback by distributed teams	0	0	0	0	0	0	0
	Total	**41**	**24**	**23**	**11**	**5**	**0**	**10**

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in 2/10 projects. Patterns in how these affordances manifest are now presented and organised chronologically by the design process phase. We see VR used with 3D models hence some affordances are recorded. However, these represent typical practices with 3D models for VR visualisation, contextualisation and testing and are therefore not novel. The use of clay modelling was not identified in any projects.

4.1.1. Initial ideation

All projects (10/10) show evidence of the affordance "Creation with dimensional understanding," which is not surprising given this is arguably the major value proposition for VR sketching. This promotes (and is therefore coded as) the use of the VR sketch platform to create 1:1 scale sketches. At the same time, we observe that traditional 2D sketching is still used in the initial idea phase for very rough sketches.

9/10 projects show evidence of students utilising visualisation affordances namely the "Holistic View" and 10/10 show the affordance "Multiple Viewpoints." We also see evidence of the inclusion of contextual features in visualisations. The manifestation of the holistic view of objects and multiple viewpoints is in the interaction with the sketch in the 3D immersive environment and the recording of multiple viewpoints from the same sketch within the logbook.

Figure 3 below exemplifies this demonstrating how a single sketch in 3D provides a holistic understanding of the design and facilitates the visualisation of the design from many different viewpoints without requiring new sketches to visualise each viewpoint.

We also saw how the holistic (3D) sketch combined with the capacity to see multiple viewpoints facilitated one designer to record how they sketched initial ideas for the vehicle interior while positioning themselves in the driver's seat (see Figure 4).

Notable is the significant number of projects (7/10) that utilise the affordance for "contextualising" that arises when using 3D sketching. This manifests both in terms of contextualising the design within an environment and adding key contextual references within the sketching environment. For example (see Figure 5), in Project 1, we see the addition of a virtual environment to check stance and balance in the initial idea instead of a paper sketch. In Project 2, the initial sketch is viewed via AR within a real street scene. In Project 6, we see the designer embedding existing components (a wheel) to reference while sketching their rough wheel concept.

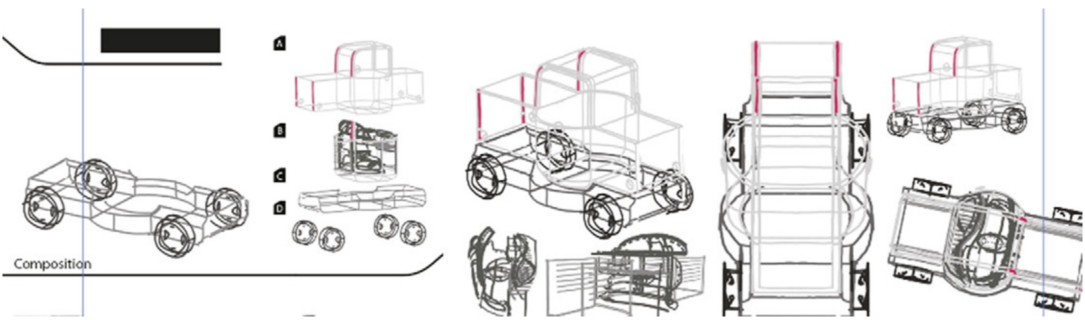

Figure 3. Examples of affordances of "holistic view" and "multiple viewpoints" in the initial idea phases of Project 2.

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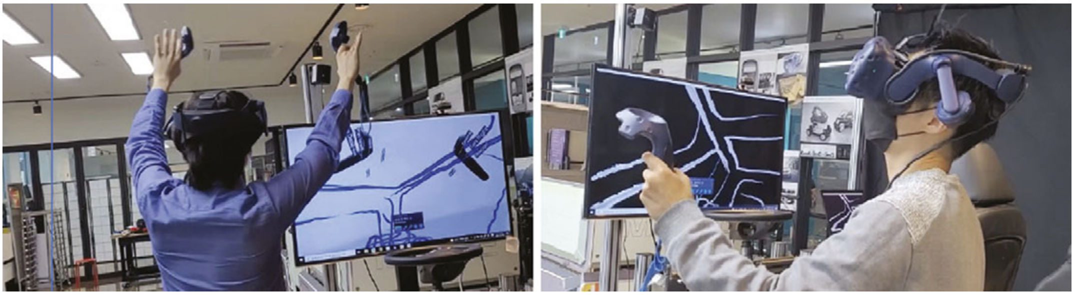

Figure 4. Images from Project 10 showing a designer sketching initial interior ideas from the position of the driver in the vehicle.

Figure 5. Affordance for visualising in/with context manifested in Project 1 (left) showing an initial sketch within a virtual environment, Project 2 using AR to visualise an initial 3D sketch within a street scene (middle) and in Project 6 (right) embedding a wheel for reference within their 3D sketch.

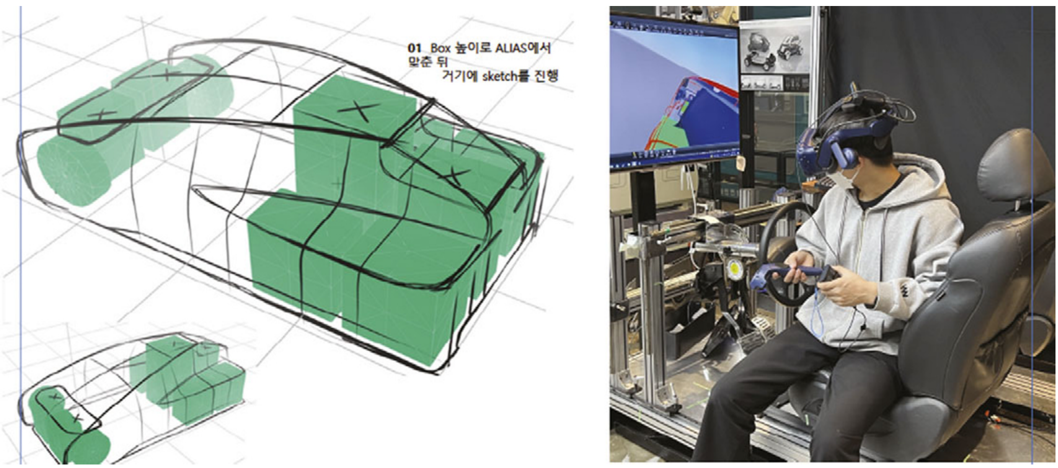

Figure 6. Example of testing sitting position with respect to cargo space during the initial ideation phase.

In some cases (3/10), we even see formalised testing occurring at this early phase of the design process. For example, we see in Project 2 how the designer uses the immersive environment to test the height of a sitting surface using the vehicle buck concurrently with testing interior cargo space (see Figure 6).

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4.1.2. Key line sketch

As with initial ideation, we see a majority of designers evidencing the affordance "Creation with Dimensional Understanding" (8/10). Similar to the Initial Ideation phase is the evidence of all three visualisation affordances. The major theme identified is the capacity to review designs at the Key Line phase in multiple viewpoints and to make immediate changes within the immersive view of the design at a 1:1 scale. These affordances manifest in the way designers can sketch key lines from one viewpoint/perspective and immediately review the design from other viewpoints (see Figure 7). We also note how the affordance "Immediacy" manifests in terms of fast iteration of changes where a 1:1 scale view is important to finesse and modify key lines as shown in Figure 8. Like findings in the Initial Ideation phase, we see some formal testing of key line placement (affordance "Testing") concerning interior space and ingress/egress (see Figure 9).

4.1.3. Ergonomic study

In this phase logbooks evidence affordances "Creation with Dimensional Understanding" (9/10), "Immediacy" of making changes (4/10), and "Testing"

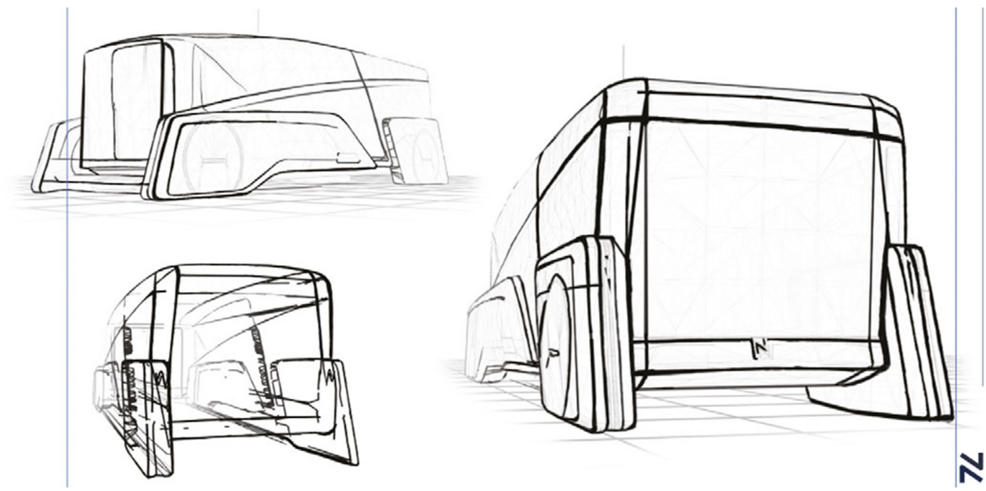

Figure 7. Examples of affordances of "creating at scale" and "multiple viewpoints" to extract key lines from initial ideation sketches during key line phases of Project 7.

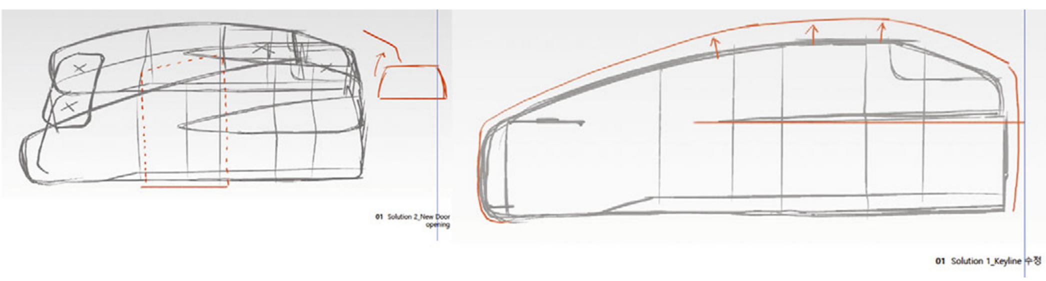

Figure 8. Examples of affordance "immediacy of change" and "multiple viewpoints" to modify the roof line.

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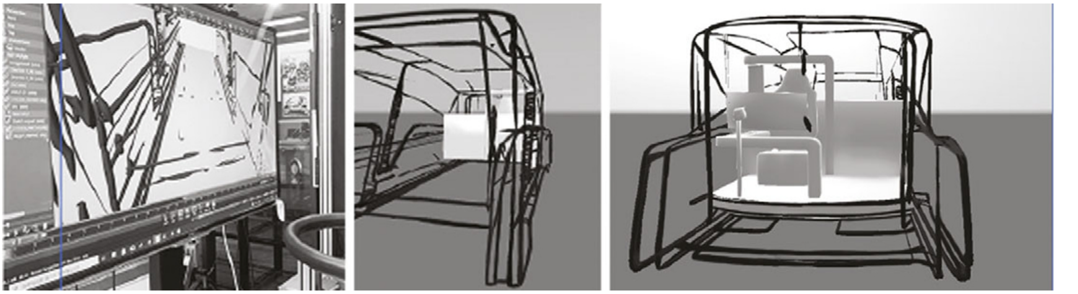

Figure 9. Example of testing interior space and features with respect to key line placement in Project 7.

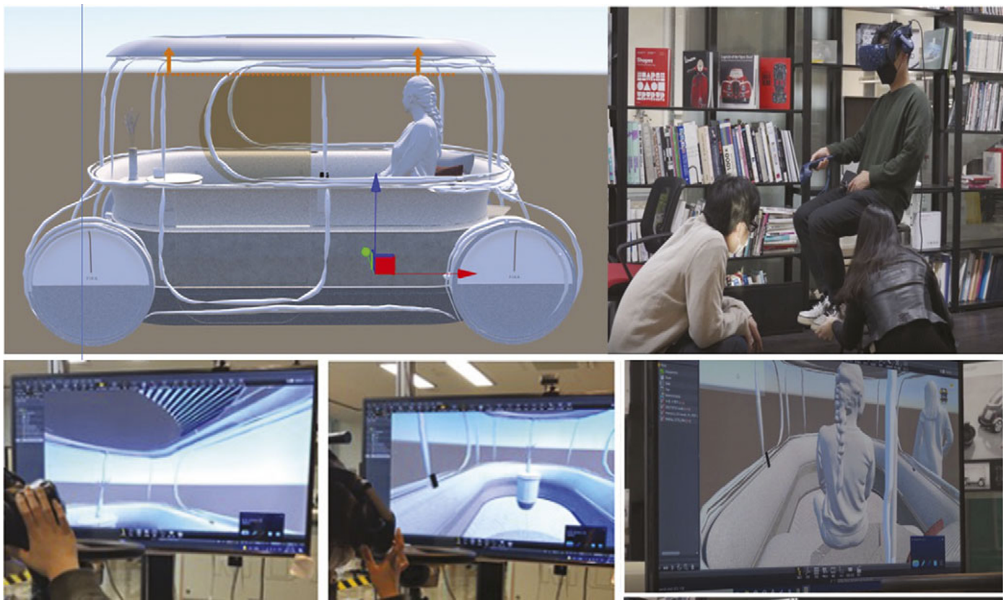

Figure 10. Examples of the affordance "integrated testing and analysis" in Project 5 testing the ergonomic qualities of the interior and capacity to make immediate changes as indicated in the top left showing the raising of the roof in response to testing.

(6/10). As per the goals of this phase, these affordances manifest in creating and testing ergonomic properties, such as driver/rider comfort in terms of headroom (see Figure 10 for example), ingress/egress and testing driver field of vision through the windshield (see Figure 11 for example).

4.1.4. Concept development

Overall fewer affordances manifest in this phase of the process. They primarily relate to the ability to further test key elements of the underlying concept in projects "Testing" (6/10). For example, Project 5 proposes an autonomous vehicle with an interior that changes to create a more comfortable interior space, which requires

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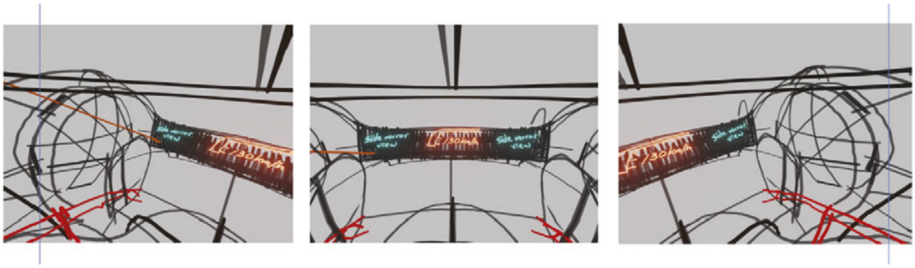

Figure 11. Example of affordance testing and analysis in Project 8 where the designer is testing the field of vision from the driver's perspective within the 3D sketching environment.

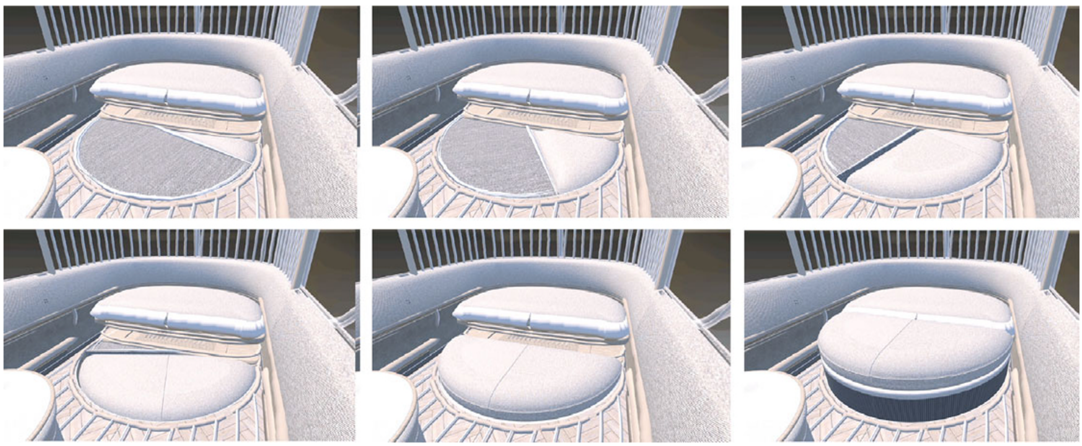

Figure 12. Sequence taken from an animation used in Project 5 to test and verify the concept of a reconfigurable interior, exemplifying the affordance of "Testing" in the concept development phase.

further development and testing to validate the plausibility of how the interior is reconfigured. Project 7 proposes a vehicle that can be used to house a pop-up café and therefore requires development to establish the viability of housing relevant components/elements. The manifestation of this "Testing" affordance is different to that seen in the ergonomic study phase. In this phase, we observe the use of animation to explore the dynamic qualities of the design. For example, Project 5 animates the 3D geometry of the sketch to show the sequence of motion and resulting volumes occupied as elements of the seat are reconfigured (see Figure 12). This relies on the 3D geometry of the sketch creating the capacity to import into 3D animation software. Hence, the dynamics of the door opening or seat moving can be animated and thus further interrogated, rather than by imagining (when sketch is used) or using a 3D model which requires a greater time investment to create before animation.

4.1.5. Presentation

In this phase, we see relatively extensive use of VR sketching for presentation and communication purposes as compared with traditional methods for this phase of the

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design process. Six out of 10 projects included VR sketching when communicating work at this phase. Affordances observed were correspondingly in the "Improved Communication and Understanding" but also "Testing," "Contextualising," and "Multiple Viewpoints." These affordances manifest in terms of animations and images including environmental or object contextual features. For example, Project 7 uses a sequence of rendered key line sketches alongside 3D model representations with figures and objects that form a storyboard to explain the use case of the design (see Figure 13). Project 4 utilises 3D sketches within the target use environment (the planet Mars) to illustrate how the vehicle would interact with a support vehicle (see Figure 14).

We note there is an overlap in terms of the manifestation of affordances at this phase with the preceding phases described above. This shows how the 3D sketches and animations created earlier have value later in the design process to communicate design intent and argue for the feasibility of a design.

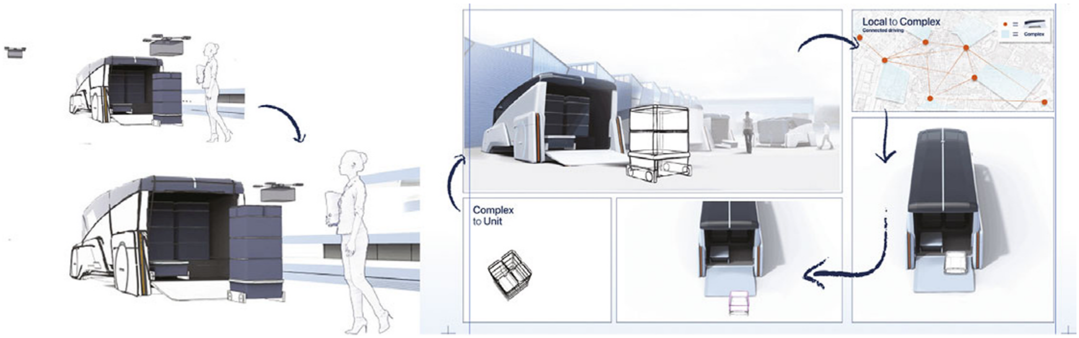

Figure 13. Example of VR sketches being used in a presentation storyboard demonstrating affordances of "Contextualising" and "Improved Communication and Understanding ".

Figure 14. Screenshots included in the logbook of project 4 exemplifying affordances "Contextualising" and "Improved Communication and Understanding" with VR sketch which is animated in context during a presentation.

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4.2. Post-project reflections

Data drawn from reflections is summarised in Table 4 and analysed below to understand the designers' perspectives on the benefits, challenges and recommended improvements for using VR sketching. The analysis is organised by trends in the affordances referenced by designers.

4.2.1. Visualisation

Where Visualisation affordances are raised, they describe efficiencies arising from a better perception of spatial qualities. For example, Reflection 2 highlights the "*Efficiency of rotating different viewpoints on the spot to understand the spatial arrangement*," and Reflection 4: *"Instant reflection and quick fidelity check on changes made as the surfaces are designed."* supporting the finding from logbooks how the 3D sketch environment has benefits in Key Line and Ergonomic Study phases.

Visualisation affordances are also referenced in terms of heightened understanding via the inclusion of contextual factors. For example, Reflection 8: "*It is timesaving allowing simultaneous development of both interior and exterior aspects*," Reflection 2: "*Ease of placing the vehicle in the environment to show how the vehicle will be used in a real-life scenario.*" This supports the finding that working in 3D is valuable in terms of designing the 3D geometry of the car but also facilitates the inclusion and subsequent testing with respect to key componentry and the operating environment.

4.2.2. Creation and configuration

Creation and configuration affordances are raised concerning time-saving in iteration and understanding of 3D qualities. Specifically, the capacity to edit and modify sketches in real-time, Reflection 6 "*The time-saving aspect achieved through the ability to work in actual scale and verify spatial positioning*" and Reflection 3 "*The ability to change and move specific details within the same sketch is a significant advantage of 3D sketching, offering designers unprecedented flexibility.*"

We also see how the ability to work at scale (affordance "Creation with Dimensional Understanding") enables unique modes of interaction with the sketch, namely the ability to position oneself within the sketch, in this case, position oneself in the driver's position Reflection 8: "*You can position the driver and design around him this was useful to type of vehicle I was developing.*" Demonstrating a

Table 4. Summary of affordances coded as advantageous in post-survey reflections

	Visualisation			Creation and configuration		Integrated analysis	Collaboration	
Code	Holistic view	Multiple viewpoints	Contextualising	Creation with dimensional understanding	Immediacy	Testing	Improved communication and understanding	Concurrent review and feedback by distributed teams
Count	3	0	3	4	5	3	1	2

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further advantage that arises from the immersive element of dimensional understanding while creating.

4.2.3. Testing

References to "Testing" affordances are closely tied to references to "Creation and Configuration" affordances. This arises from the consistent view that creation at scale (affordance "Creation with Dimensional Understanding") enables efficiencies in terms of faster and more frequent iteration between testing and subsequent modification, for example, Reflection 4 "*It was easy to check the feasibility regarding scale and ergonomics. It simplifies the process of evaluating feasibility concerning scale and ergonomics*" and Reflection 6 "*It helped accelerate the verification phase which made design process efficient.*" This aligns with findings concerning the Ergonomic Study and Concept Development phases, namely faster preliminary verification without the need to invest in 3D or clay modelling.

4.2.4. Collaboration and communication

Coding of affordances for collaboration and communication is a point of difference between data captured in logbooks versus reflections. This is potentially explained as logbooks being a relatively personal record of work and hence not capturing points of collaboration. Positive statements on communication highlight the ease of communicating designs and ability to review for example Reflection 5 "*Facilitation of seamless communication when sharing ideas among collaborators. These tools enable individuals to easily convey their concepts, even in the early rough phases of development.*" Reflection 7": *It was great to work collaboratively in the 3D space.*" As seen in logbooks, we see references to communication affordances via storyboard mode of presenting designs leading to positive views on communication in terms of storytelling. For example, Reflection 8: "*I found it useful to use it for storytelling in 3D space*" and Reflection 6: "*Help create storyboards that closely resemble reality, streamlining the design process and enhancing overall accuracy.*"

4.2.5. Barriers and recommendations

As shown in Table 5, the two challenges referenced most frequently and thus also the basis for improvement were "Precision" and "Compatibility." Challenges concerning "Precision" were largely related to the precision with which VR

Table 5. Frequency of codes relating to barriers and recommendations identified in reflections

No.	Code	No. designers referencing challenges	No. designers referencing improvements
9	Precision	4	3
10	Training	0	0
11	User interface	2	4
12	Compatibility	4	5

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sketching could create and modify lines due to inherent limitations in stylus tracking. For example, Reflection 1 "*Difficulty in detailing certain surfaces and a lack of precise iterations are two common challenges*" and Reflection 2 "*Hard to detail complex surfaces with lack of stroke options.*" We also see a reference to precision for making edits to stroke/line position, Reflection 8 "*Couldn't adjust exact measurement when fixing the data so I had to work on these details through other programs when required fixing.*" This highlights a potential inefficiency for example Reflection 3: "*It took longer to define the key line when using [VR sketching] than traditional sketching as I found brush tools in [VR sketching] not as accurate.*" We note how the concerns about precision are closely related to User Interface as challenges in precision are directly connected with suggestions on interface approaches to improve the issue. Such improvements relate to greater precision around curve creation and editing for example Reflection 1 "*more variety of brush tools especially when articulating curved surfaces*" and Reflection 6 "*layers to help create better curved surfaces.*"

Challenges concerning "compatibility" revolve around compatibility and capacity to transition designs and embodied data between different software as the design evolves. For example, Reflection 3 "*Having to import the data to other software was a time-consuming process*" and Reflection 5 "*Importing and exporting data from Feather to Alias was not smooth.*" There were also several references to data import and export being a key point for improvement, for example, Reflection 5 "*smoother transition between programs,*" Reflection 2 "*Currently Feather data needed to import into Alias and Keyshot for further detailing*" and Reflection 7 "*Better importing data between programs.*" The key takeaway from this trend is that while the burden of tool switching is lessened by having 3D geometry from VR sketches, the limitations of software mean there is still time embodied in transitioning from 3D sketch to 3D modelling.

We note training was not explicitly referenced as a challenge or area for improvement. We contend this is potentially explained by designers having ample time to train and develop a threshold skill with VR sketching. As such, we contend the concern seen in the literature (Jin & Lee 2019; Maurya *et al.* 2021; Oti & Crilly 2021; Zou *et al.* 2023) was not expressed as designers were not required to decide on the cost–benefit of whether the time spent training was worth the outcome during the design process. Furthermore, we contend the learning curve is not insurmountable since students (having had ample opportunity to train) rarely made any comment on their skill to execute.

4.3. Survey

Data from the survey is now presented contrasting average Likert scale ratings of VR sketching and traditional sketching (Figure 15).

Overall, we see how ratings for VR sketching are more positive and therefore viewed to outperform traditional sketching except for the Sketch Speed criteria. The view that traditional sketching is faster explains the use of traditional sketching in the earliest phases of Initial Ideation where the largest volume of ideas is required at the lowest fidelity. Relatedly, the rating of Sketch Accuracy as higher with VR sketching aligns with the benefits in terms of elevating fidelity when using VR sketching in early phases. We note though the distinction between accuracy and precision with respect to the transition from VR sketch to 3D modelling. While accuracy is heightened

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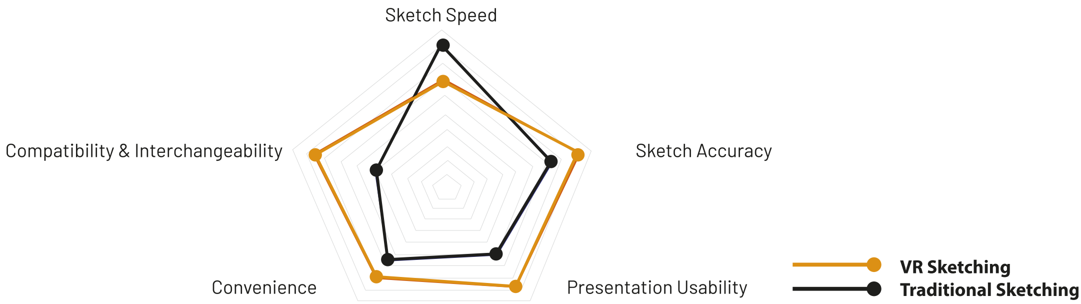

Figure 15. Survey data contrasting qualities of VR sketching with traditional sketching.

compared with traditional sketching there are still limitations in terms of precision which necessitate using 3D modelling to further develop the design as per comments in reflections 3 and 8 (see Section 4.2). The superior rating for Presentation Use aligns with findings from logbooks and reflections further supporting the value of 3D sketch geometry in creating animations and storyboards. Findings for greater convenience align with earlier findings about the value of working in 3D in terms of time savings with respect to needing to create multiple 2D sketches to depict 3D forms, or the need to update multiple elevation views corresponding to design changes such as key line placement. The finding for Compatibility and Interchangeability is interesting as one hand it aligns with the findings from logbooks emphasising the value and compatibility of 3D sketch geometry to contextualise with environments or other 3D models. On the other hand, designers' greatest frustrations and area for improvement in reflections is the compatibility at this phase/action. Ultimately, we contend the finding highlights the massive increase in compatibility compared with sketching, notwithstanding that file import/export to tool switch to 3D modelling environments could be smoother.

In general, the survey findings are valuable in supporting the themes emerging from logbooks and reflections. They highlight relatively well-rounded benefits/positives of VR sketching, highlight the basis for continuing to use 2D sketching in the earliest phases based on speed and the greatest improvement/positive being compatibility and utility of 3D sketch geometry for later phases (3D modelling and eventually presentation).

5. Discussion

In this section, we return to the underlying research goal to understand How VR sketching can be integrated within the concept design process and how affordances of immersive VR 3D sketching identified in the literature manifest in the concept design process. This is organised by first discussing results to illustrate how affordances manifest in the design process, the benefits of VR sketching design process and implications for concept design processes.

5.1. Manifestation of affordances and design process advantages

An overview of how affordances manifest in the design process responding to research questions 1 and 2 is compiled in Table 6. We use fidelity as the key variable

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Table 6. Synthesis of manifestation of affordances, corresponding level of fidelity observed, design verification, process advantage and limitations

	Initial Ideation	Key Line	Ergonomic Study	Concept Development	Presentation
Manifestation of Affordances	Capacity for multiple viewpoints and immersive review Capacity for the addition of context	Capacity for multiple viewpoints and immersive review Capacity for the addition of context Immediacy of design edit and review.	Capacity for multiple viewpoints and immersive review Capacity for the addition of context Immediacy of design edit and review.	Capacity for animation and dynamic review Capacity for the addition of context Immediacy of design edit and review.	Capacity for multiple viewpoints and immersive review Capacity for the addition of context Capacity for animation
Fidelity Comparison	Heightened spatial and environmental fidelity via immersive 3D environment & geometry	Heightened spatial and environmental fidelity via immersive 3D environment & geometry	Heightened spatial, environmental, and operational fidelity	Similar or lower spatial, environmental, and operational fidelity	Lower spatial, environmental, and operational fidelity
Design Verification	Verification of basic spatial volumetric qualities	Verification of key lines with a richer understanding of the design with 3D geometry	Verification of ergonomics with a richer understanding of the design with 3D geometry and exterior with interior component integration	Verification and development of the concept in terms of overall function	Verification and presentation of user experience and concept narrative
Process Advantage	Reduced requirement for a multitude of sketches to communicate ideast	Reduced need to update elevation views enabling faster iteration	Reduced need to update elevation views enabling faster iteration	Delayed and/or reduced investment in 3D modelling and clay modelling	Reduced requirement for (high-fidelity 3D models and clay models) for presentation
Limitations	Traditional sketching is faster for representing individual sketches/views of basic ideas	Potential limitations in precise line/curve manipulation	Potential limitations in stakeholder review requiring VR equipment vs. 1:1 drawings pasted on walls	While spatial fidelity is greater, 3d modelling software could offer greater precision in contextualising components	Presentations relying solely on VR sketches would inadequately communicate realism in appearance.

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by which to discuss the artefacts/visualisations created with respect to corresponding verification that can be achieved when using VR sketching within a given design process phase.

In initial ideation, we see VR sketching is advantageous in verifying design in terms of scale, proportion and spatial qualities as per extant literature (Rahimian & Ibrahim 2011; Jin & Lee 2019; Oti & Crilly 2021). We can see how the 3D environment and resulting geometry facilitate greater understanding via the immersive and holistic view of the sketch (Lee *et al.* 2019; Zhang *et al.* 2020; Ranscombe *et al.* 2023). A key novel finding is the capacity to integrate contextual features. These manifestations of affordances lead to a process advantage via verifying aspects of the design that would previously require 3D modelling or clay modelling but with less effort expended as the overall fidelity remains low. This can be viewed as advancing some aspects of design fidelity while keeping others comparatively low. Specifically, we see how the spatial fidelity (representation of volumetric proportions), and environmental fidelity (representation of the product environment and contextual elements) (Cox *et al.* 2022) are heightened while overall design fidelity remains low in the form of line sketches. As such we see how the avoidance of a large volume of 2D sketches and delay of 3D modelling that would otherwise be needed to attain this level of understanding.

In Key Line and Ergonomic Study phases, we note the fidelity becomes less advanced than when using VR sketching for initial ideation. This is because traditional processes already work at a 1:1 scale in this phase. However, here we note working with these sketches in 3D does afford somewhat advanced fidelity in terms of realising sketches such that multiple viewpoints and angles can be perceived as per Rahimian & Ibrahim (2011). It also leads to the primary process improvement as there is no need to spend time updating corresponding views. Furthermore, the simplicity and sketch-based input enables faster editing and iteration of designs. In the Ergonomic Study phase, this advantage extends to enabling better integration of interior, exterior and key componentry. As such we see how the use of VR sketching in this phase enables heightened spatial fidelity but also operational fidelity (representation of intended functional operation) (Cox *et al.* 2022) without the requirement to engage in 3D modelling. Here, as with the Initial Ideation phase, we see an advanced understanding and thus verification all while using a flexible sketch-based input that also delays the need for 3D modelling and clay modelling.

In concept development, we see an interesting "tipping point" in terms of overall design fidelity. In this phase, the overall fidelity of designs is similar to if not lower than the fidelity dealt with in a traditional automotive concept design process where rendered sketches and 3D modelling are used concurrently. This leads to designers being able to develop and verify the concept in terms of operational fidelity while again delaying investment in 3D modelling/clay modelling. Enabling this is the capacity for the 3D sketch to be animated and viewed dynamically to provide necessary verification.

We also see comparatively lower fidelity visuals than the traditional process in the Presentation phase. However, here we do not see a delay in investment in higher fidelity. 3D models and clay are still essential in this phase to reach precision that VR sketching is not able to easily create (see Barriers and Recommendations in Section 4.2), and that is essential to advance towards manufacturing/development. Instead, we see the utilisation of low-fidelity developmental visuals used in service

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of storytelling. As with other phases, we see how the 3D sketch enables contextualisation, and animation while the immersive view enables the creation of storytelling assets such as storyboard frames (environmental and operational fidelity) as per Rodda *et al.* 2022. Thus, we contend while overall fidelity is lower, the capacity for communicating experience richly at this lower level of fidelity is the primary process and efficiency gain.

5.2. Benefits of VR sketching enabled design process

Based on the discussion in the previous section, we can now address research question 3 (How does a VR sketch-enabled concept design process model compare with a traditional concept design process model?). We use Figure 16 to contrast the process involving VR sketching with the traditional process with traditional tools and outline the generalisable benefits of VR sketching.

An overarching theme in findings was the capacity to test and verify aspects of the design sooner based on achieving heightened spatial, environmental and operational fidelity via VR sketching. We frame this as the VR sketching facilitating a leap forward in understanding that would usually require more time investment in a greater volume of sketch visualisation, or investment in 3D modelling and/or clay modelling. This leap is exemplified in Figure 16 by the comparative increase in fidelity between VR sketching and traditional approaches to Initial Ideation, Key Line and Ergonomic Study phases. As such we see how a greater degree of verification can be reached sooner in the design process which corresponds to engaging each subsequent phase sooner in the process. This is illustrated in Figure 16 by the position of phases occurring sooner in the project duration (Y axis) compared to the traditional process equivalent. This ultimately suggests a reduction in the design effort required to progress to the next phase as demonstrated by the reduced number of initial ideation sketches, key line sketches and ergonomic study sketches.

We find that VR sketch phases reach a “ceiling” in fidelity around the Concept Development phase and before 3D modelling. At this point, it is still essential to engage traditional design tools (3D modelling and clay modelling) to develop fidelity of the aesthetic and overall form in terms of precise surfaces to complete the concept design process. The concept of the fidelity “ceiling” is worth noting as it also dictates the level of resolution of precision that is achievable when designs are being verified. Specifically, the level of testing and verification achieved can be described as preliminary validation or qualitative review, providing an approximate yet sufficiently accurate assessment of overall form and proportion.

A limitation in our findings relates to a lack of findings concerning collaboration affordances. While literature highlights the potential of VR sketching to support collaborative design, we saw relatively few references to these affordances within our data. We do not contend these affordances are not realised, rather projects being conducted individually combined with the focus on logbooks for analysis led to a concentration on the affordances that support the designer when working individually. “In a similar vein, the longitudinal approach and focus on visualisations as the data source limited the extent, we could analyse the possibility of design fixation occurring Further discussion of these limitations and proposals for future research is given in Section 5.4.

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5.3. Implications for industrial design

Developing fidelity (spatial, environmental and operational) sooner during early phases is the overarching benefit demonstrated which we argue will translate across a spectrum of industrial design applications. However, we also acknowledge that advancing fidelity could have an impact on design fixation. It is possible that greater fidelity and quicker testing and verification might reduce exploration and heighten the chances of design fixation. Conversely, it could be argued the reduced effort in creating a multitude of sketches and updating elevation views creates a greater scope to explore more ideas and iterate between design phases. Ultimately, further research is needed to understand whether the advanced spatial, operational and environmental fidelity influence design fixation or make more time to explore a breadth of early ideas.

The heightened ability for iterations also implies the need for those developing VR sketch platforms to emphasise compatibility. As shown in reflections, designers were at times critical of the capacity for tools to work seamlessly with 3D modelling, Thus, a key implication is that greater iteration puts greater emphasis on fast and seamless tool switching. Concerning designers' adoption of the tool, our study shows how VR is distinct from traditional 2D sketching in terms of appearance. We see how comparatively crude 3D sketches have immense use in the early phases as well as when presenting finalised concepts. To designers considering adopting VR sketching this implies modes of use but also demonstrates where expectations of what a 3D sketch output should look like. Namely, they need not be concerned about the "look" as the tool does not replace traditional tools that generate the highest fidelity, rather that it can be used to reach a phase of implementing said tools with comparatively less effort expended on traditional sketching (as highlighted in Figure 16).

5.4. Limitations and further work

A key limitation to our findings stems from the specific context of our case studies being a single automotive concept design process applying one VR sketching

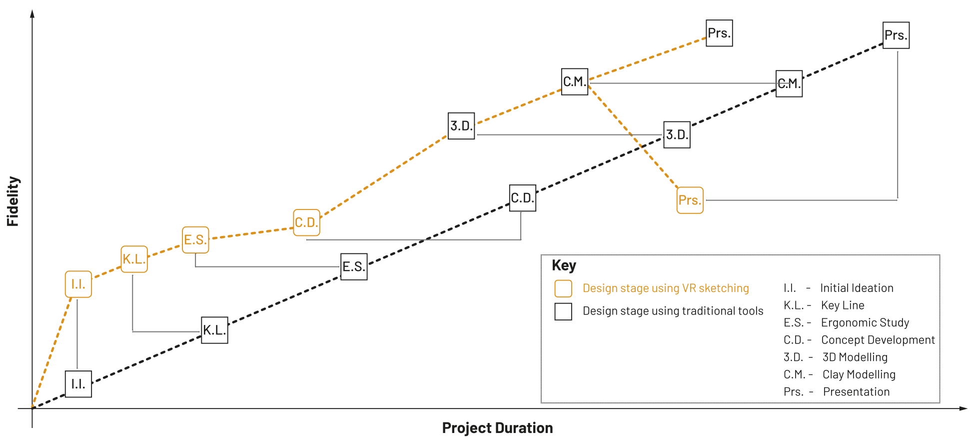

Figure 16. Visual comparison of VR sketch concept design process contrasted with the typical concept design process in terms of design fidelity and timing of project phases within the overall project duration.

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platform (Feather). Hence, we acknowledge there may be nuanced differences in the way affordances lead to process advantages in the context of different product design processes. As such, this limitation needs to be considered with respect to the generalisability of our findings. Nevertheless, we contend certain advantages observed in the findings transcend product, process and tool boundaries. Namely, how VR sketching with heightened spatial and environmental fidelity is advantageous for almost any industrial design project to verify ergonomic considerations and to contextualise the product within its intended environment. Likewise, the heightened operational fidelity afforded through the dynamic qualities of VR sketches would be advantageous when designing products with moving parts or components. Furthermore, these benefits do not arise from the nuanced qualities of the VR interface or workflow; rather, they stem from the fundamentally immersive and true-to-scale qualities of VR that exist in all VR sketching tools. At the same time, we do acknowledge advantages, such as the benefits of faster iteration during key line and ergonomic study phases, which may vary depending on the tool's ease of use and designers' skill. Nonetheless, we contend our findings and proposition for how the concept design phase changes when using VR sketching will hold in many product design projects ergonomic factors are significant and scale is not readily experienced via computer screen or sketch pad.

A second limitation relates to our participant sample. We acknowledge that our sample comprises junior designers and the context of projects being academic hence it is possible that senior designers with extensive experience engaging in live industry projects could lead to different findings. However, as stated in Section 3.3, we argue that the close association with industry partners Hyundai and Kia combined with the guidance of senior industry advisors assures that the process followed is an adequate reflection of industry projects. Concerning skill, we acknowledge that our sample possesses less experience in terms of design skills. For this limitation, we first argue that VR sketching is a relatively novel tool and hence a sample of experienced designers would have the same level of experience with the tool. Different advantages may arise because senior designers have more advanced skills and greater resources with the traditional tools that VR sketching is used alongside. For example, a highly experienced 3D modeller may be able to create 3D models very quickly and hence process advantages from the speed of VR sketching may be less pronounced.

Finally, we acknowledge the limitations arising from our reliance on logbooks as the primary data source. While logbooks present a rich and unobtrusive method for investigating the application of design tools and their resulting visualisations (see Sections 3.1 and 3.5), they can omit insights that might surface through real-time feedback or direct observation. As such, we recognise that our method does not permit a fine-grained analysis that captures the evolution of ideas and design cognition as they happen, that is, abductive reasoning that occurs with them or the possibility of design fixation. Although designers almost certainly engaged in creative leaps, the logbooks and retrospective interviews record outcomes rather than the cognitive moves that produced them. This underscores the need for complementary data collection methods, such as screen recording VR interactions, or video capture of design activities and think-aloud

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protocols, to capture tacit design activities that participants may not document in logbooks.

In light of these considerations, future research should broaden its scope beyond automotive concept design and include more experienced designers working on diverse projects. Likewise broadening the data collection methods to include screen recording, video observation and think-aloud protocols would be of value to achieve a more fine-grained analysis of the evolving utility and limitations of VR sketching. Thus, we propose future studies on the utility of VR sketching and other emerging technologies alike should adopt a mixed-method or longitudinal approach to enhance the robustness of findings. Enabling researchers to triangulate key visualisations with data from direct observation, logbooks and continuous participant reflections would offer a more comprehensive understanding of how VR sketching integrates into professional design workflows over time.

6. Conclusion

Virtual reality has for some time been integrated within design processes to review products at scale and within immersive environments. The next iteration, VR sketching, enabling sketch-like creation whilst immersed in a virtual environment with the sketch is now commercially available and accessible to designers. Extant research highlights the wide-ranging benefits of using VR sketching to advance through the design process with less investment in 3D modelling and physical prototypes. However, extant research uses controlled experiments or short-term case studies, leading to a substantial gap in understanding how VR sketching can be best implemented within design processes for designers harnessing the proposed benefits. Addressing this gap our paper analyses the sustained use of VR sketching implemented in 10 automotive concept design projects each conducted over 10 months. Through analysis of designers' logbooks capturing design development supported by post-project reflections, we gain a comprehensive understanding of how positive affordances manifest in practice and turn present how the design process changes. Specifically, we show how and when designers can exploit the creation of simplified 3D geometry embodied in VR sketches to advance the design process in terms of several dimensions of design fidelity. We highlight where process advantages are realised through (1) increased spatial fidelity, reducing the time required to iterate 2d sketches, (2) operational fidelity supporting dynamic testing of concept functionality via animation and (3) environmental fidelity supporting contextualising components but also storytelling when presenting designs.

As such, we contribute to the aforementioned research gap by explaining how affordances can be realised in terms of design fidelity and the phase of the design process where they can be harnessed to improve the conceptual design process. Concerning theory, we characterise the types of fidelity that VR sketching supports in various stages of the concept design process. In doing so, we contribute to knowledge on design tools and process management with invaluable insights into the effective integration of VR sketching tools in the product development process.

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