# Material Visualisation for Virtual Reality: The Perceptual Investigations

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor in Philosophy

By

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# Abstract

Material representation plays a significant role in design visualisation and evaluation. On one hand, the simulated material properties determine the appearance of product prototypes in digitally rendered scenes. On the other hand, those properties are perceived by the viewers in order to make important design decisions. As an approach to simulate a more realistic environment, Virtual Reality (VR) provides users a vivid impression of depth and embodies them into an immersive environment. However, the scientific understanding of material perception and its applications in VR is still fairly limited. This leads to this thesis's research question on whether the material perception in VR is different from that in traditional 2D displays, as well as the potential of using VR as a design tool to facilitate material evaluation.

This thesis is initiated from studying the perceptual difference of rendered materials between VR and traditional 2D viewing modes. Firstly, through a pilot study, it is confirmed that users have different perceptual experiences of the same material in the two viewing modes. Following that initial finding, the research investigates in more details the perceptual difference with psychophysics methods, which help in quantifying the users' perceptual responses. Using the perceptual scale as a measuring means, the research analyses the users' judgment and recognition of the material properties under VR and traditional 2D display environments. In addition, the research also elicits the perceptual evaluation criteria to analyse the emotional aspects of materials. The six perceptual criteria are in semantic forms, including rigidity, formality, fineness, softness, modernity, and irregularity.

The results showed that VR could support users in making a more refined judgment of material properties. That is to say, the users perceive better the minute changes of material properties under immersive viewing conditions. In terms of emotional aspects, VR is advantageous in signifying the effects induced by visual textures, while the 2D viewing mode is more effective for expressing the characteristics of plain surfaces. This thesis has contributed to the deeper understanding of users' perception of material appearances in Virtual Reality, which is critical in achieving an effective design visualisation using such a display medium.

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The four-year study career is coming to an end. Looking back on the learning and research process in recent years, I can confidently say that I am lucky. I want to thank some people here. Their support, help, and kind understanding have made me happy and warm throughout my Ph.D. studies.

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# Publications and Author's Contributions

The publications resulted from this thesis's work and their related chapters

- *Journal articles*

1. Niu, M., & Lo, C. H. (2022). Do we see rendered surface materials differently in virtual reality? A psychophysics-based investigation. Virtual Reality (SCI), 1-15. https://doi.org/10.1007/s10055-021-00613-3 (Chapter 4)

- *Book Chapters*

2. Niu, M., Lo, C. H., Barrett, R., Yong, Y., & Liu, B. (2021). Material visualisation and perception in virtual environments. In Materials Experience 2 (pp. 135-139). Butterworth-Heinemann. (Chapter 5)

- *Proceedings and Conference contributions*

3. Niu, M., & Lo, C. H. (2019, July). An investigation of material perception in virtual environments. In International Conference on Applied Human Factors and Ergonomics (pp. 416-426). Springer, Cham. https://doi.org/10.1007/978-3-030-20476-1_42 (Chapter 3)

4. Effects of Roughness and Texture on Surface Material Perception in Virtual Reality: The Psychophysics Approach, published in International Conference on Computational & Experimental Engineering and Sciences ICCES Online (ISSN: 1933-2815) (Chapter 5)

- *Extended Publications*

5. Niu, M., Lo, C. H., & Yu, Z. (2021). Embedding Virtual Reality Technology in Teaching 3D Design for Secondary Education. Frontiers in Virtual Reality, 2, 661920. https://doi.org/10.3389/frvir.2021.661920

6. Yu, Z., Lo, C. H., & Niu, M. (2021, November). Developing a Virtual Reality-Aided Learning Space for Secondary Education: The Service Design Approach. In Proceedings of the Future Technologies Conference (pp. 416-431). Springer, Cham. https://doi.org/10.1007/978-3-030-89912-7_32

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# List of Abbreviations

| | |
|---|---|
| PD | Participatory Design |
| CAD | Computer-Aided Design |
| 3D | Three-Dimensional |
| 2D | Two-Dimensional |
| VP | Virtual Prototyping |
| VE | Virtual Environment |
| VR | Virtual Reality |
| HMD | Head-Mounted Display |
| BRDF | Bidirectional Reflectance Distribution Function |
| IVR | Immersive Virtual Reality |
| KE | Kansei Engineering |
| JND | Just Noticeable Difference |
| CHG | Construction History Graphs |
| CAVEs | Cave Automatic Virtual Environments |
| F-ANOVA | Factorial-Analysis of Variance |
| SD | Substance Designer |
| UE4 | Unreal Engine 4 |

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# Chapter 1 Introduction

## Section 1.1 Background and Motivation

The accurate representation of materials is an important factor for obtaining high-quality visualisation (Okuyan *et al*., 2014). As one of the key elements in design expression, materials are nowadays rendered in a digital context to significantly enhance the visual appearance of objects in virtual scenes (Hatka & Haindl, 2012). The rendering refers to the virtual lights interacting with the surface material of the product model to reveal its physical shapes, thus creating a realistic representation of product prototypes (Keller *et al*., 2015; KT *et al*., 2019). As a result, the visual impact of the rendered outcome is heavily reliant on a designer's ability to replicate real-world elements in the scene. In the field of industrial product design, CMF refers to colour, material, and finishing technology, which play together to meet the design needs and decide the primary user experience (Becerra, 2016). Previous studies often focused on the effect of colours, and the visualisation of material characteristics has not received the equal attention in the field of design research (Di Cicco *et al*., 2021). Veelaert *et al*. (2020) believed that as an integral part of products, materials visual perception contributes to the function and significance of products in the design and development stage. In fact, the visual perception of materials depends not only on their shapes and colours but also on the properties or components that they are made of (Adelson, 2001; Marlow *et al*., 2006; Kentridge *et al*., 2012).

Most objects are predominantly perceived by our visual systems (Schifferstein & Cleiren, 2005; Schifferstein, 2006; Tiest & Kappers, 2007). That seems to explain why most designers consider visualisation techniques very important because they guide the aesthetic expression of products and provide cues to subsequent interactions between the products and their users. Related studies suggested that designers should integrate the consideration of materials in the early stages of design process, which is beneficial to the design results (Van Kesteren *et al*., 2007; Ashby & Johnson, 2013). On the other hand, Piselli *et al*. (2018) argued that the current methods of material visualisation were not relevant to the established design procedures, and the research on material visual perception lacked equivalent data support and well-defined procedures to specify user experience. Indeed, material experience can be compelling and complex (Karana *et al.*, 2016), which may be varied with contexts related to products such as the use scenarios and a users' cultural background.

Due to the iterative nature of design process, any modification of the design scheme involves evaluating and improving numerous solutions for product final forming (Antonya & Talaba, 2007). During those interactions, product designers and developers expect presentation tools to provide them with the data and information needed for making intermediate design decisions. At present, the mainstream material visualisation approach in the design field is to use Computer-Aided Design (CAD) tools to draw virtual 3D models from the conceptual sketches and attach the visually near-real colour and material parameters to the model. This process helps transform the design concept from 2D illustrations to 3D models and achieve a good expressive fidelity of design. However, as a visualisation tool developed for traditional desktop devices, the projected 2D views provided by CAD tools has obvious limitations such as hidden surfaces. Although the 3D data are embedded in the components in CAD applications, the user interaction with those components has not changed significantly (Baumgartner *et al.*, 2015). Multiple scholars suggested using Virtual Reality (VR) technology with intensive immersions to support scientific visual analysis. Kim & Nam (2014) pointed out that VR, as an immersive medium, can simulate the physical presence of users in the natural and imaginary world. Moreover, some researchers stated that the traditional 2D visual input device (screen) was not sufficient for manipulating 3D objects in the virtual space (Strauss *et al.*, 2002). The non-immersive visual interaction system is clumsy and unnatural (Stannus *et al.*, 2011). Designers tend to be skilled in CAD tools and have long been accustomed to this visual interaction mode. However, this may not be the case for the other stakeholders such as product users involved in design evaluation. The 2D viewing mode is not intuitive enough, and it is still not conducive to the full display of the 3D model of a product (Wang, 2002).

Virtual Prototyping (VP), a related product development approach that aims to simulate the design effect with similar fidelity to the physical prototypes so that individuals can interact and evaluate the design scheme in the virtual environment (Haug *et al.*, 1997; Choi & Chan, 2004; Choi & Cheung, 2005; Bordegoni *et al.*, 2006a; Kuo & Wang, 2007). When generating virtual prototypes, although an immersive environment is not always necessary, the dimensions of virtual prototypes need to be specified accurately. The successful VP, which shortens the time between the optimisation and the realisation of the 3D model, can help reduce the cost of product development (Bourdot *et al.*, 2010). VR is naturally a medium to present virtual prototypes with immersive and interactive viewing features. The head-mounted display (HMD) provides its users with high immersion and creates a unique visual experience. It also offers new modes of the interaction between users and 3D models (Deisinger *et al.*, 2000), especially for understanding and exploring the complex 3D structure in the display space (Grant & Lai, 1998; Ritchie *et al.*, 2002; Sánchez-Segura *et al.*, 2004, Laha & Bowman, 2012). Various studies emphasised that a more natural and realistic experience of VR is inseparable from the extra support of multi-sensory interactions such as touch and body interaction (Lee *et al.*, 2006; Mitra & Acharya, 2007; Laycock & Day, 2007; Bowman *et al.*, 2008; Schissler *et al.*, 2016; Carvalheiro *et al.*, 2016).

To sum up, in the context of CMF design, material visualisation supports the expression of design concepts and the communication of design intentions. Most studies in material perception used 2D images as the test stimuli or 2D display medium, whilst VR is advantageous in providing an immersive and arguably more natural setting for evaluating material properties. It remains unclear that whether the findings based on the traditional 2D viewing environment can be generalized to the VR viewing environment. This thesis is thus positioned at the intersection of material visualisation, user perception and VR (shown in Figure 1.1). The following section will specify the aims and contribution of this research.

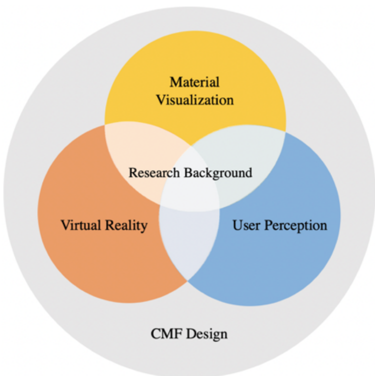


*Figure 1.1. Research Background.*

## Section 1.2 Research Aims and Objectives

### Section 1.2.1 Aims

One must not omit an important feature of VR in addition to its immersive experience: the stereoscopic depth effect. Human stereo vision is formed with two slightly shifted physical images projected on the two retinas. The visual processing areas in the brain fuses the information in the two retinal images to form a 3D sense of the visual field. VR's HMD achieves this visual parallax through delivering different image frames via the left and right lenses. Traditional 2D viewing mode is lack of this stereoscopic experience because the left and right eyes see the same, single image. Although VR is often criticised for its imperfect technology, which cannot completely replace traditional equipment (Martin *et al*., 2017). The rational use of VR as a visualisation tool can virtually alleviate the waste of costs and ineffective testing process. This study advocates that VR has unique advantages, especially in perceiving materials that need to be clearly and accurately identified. The aims of this thesis are as follows:

> *Aim 1: To explore the differences in surface material perception between traditional 2D viewing mode and immersive VR viewing mode in the real-time rendering environment.*

Generally speaking, the desktop 2D display is relatively easy to use and cost-effective. Immersive VR display mode can produce a high sense of immersion, but it also puts forward requirements for specific space and equipment (Mujber *et al*., 2004; Fairén *et al*., 2004; Hoffmann *et al*., 2006). The first aim is to confirm whether there are perceptual differences under the two different viewing conditions (VR and desktop 2D).

> *Aim 2: To specify and measure how the perceived differences are correlated with the properties of rendered material under VR and traditional 2D viewing conditions.*

The previous sections have addressed that the material visualisation effect reflects the simulation of material physical properties in the process of design evaluation. Designers need to be familiar with the impacts of materials under different display modes in order to present appropriately the design schemes. Therefore, measuring the difference in visual effects of material properties helps explain the perceptual impact provided by the two viewing modes.

> *Aim 3: To suggest how VR can be used as a design evaluation tool that reveals a greater degree of perceptual characteristics of materials.*

With the aid of VR technology, the design expression and user perception are connected immersively, forming a more fluid and intuitive process for design evaluation. The perceptual characteristics of materials in the VR environment, therefore, provide further insights on how a design concept shall be expressed in such an immersive medium.

### Section 1.2.2 Research Question and Hypotheses

In the process of selecting materials, designers usually consider the experience of the combination of physical entities (physical properties) and intangible features (visual perception) of materials (Karana *et al.*, 2010). Designers often need a reliable visual presentation approach to convey the intended design ideas. In fact, people can recognise and analyse the characteristics of materials only from vision. The so-called "seemingly authentic experience" of VR is an interesting topic for whether the display of material properties is fully presented. As a designer, the use of tools assists the smooth implementation of the design process. The key to design evaluation is whether users can accurately perceive the design effect presented by the design tools. The inquiry of this thesis thus begins with how VR, as a visualisation tool, can help designers determine the most appropriate presentation effect for the design concept.

According to Fleming (2017), the author clarified the workflow of the visual system in the process of users' materials perception, as shown in Figure 1.2. This thesis, therefore, analyse and compare the differences in users' perception experience of materials, judgment and recognition of material attributes, and emotional responses under different viewing modes based on the perceptual content in three visual stages. The viewing modes are provided by two types of devices: VR and the traditional 2D viewing mode.

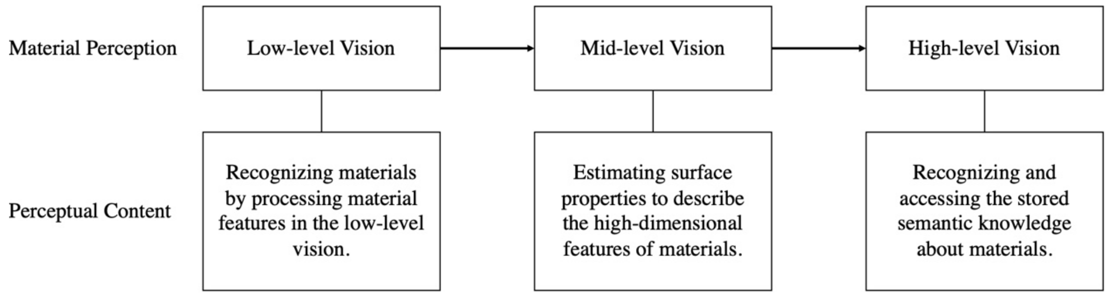


*Figure 1.2. Material Perception Process in Visual System.*

The primary research questions of this thesis are:

> *"Do users perceive material appearances differently under VR viewing and traditional 2D viewing conditions? And more specifically, how do those differences manifest through measurable perceptual and emotional responses invoked by materials presented in VR and 2D displays?* "

Our series of investigations follow the perceptual process introduced earlier, the primary research question can thus be broken down into the following sub-questions, which are explored in sequences in later chapters:

- *In the VR environment, whether users' perception of materials is different from the traditional 2D viewing modes?*

- *Where does the difference lie between users' judgment of material properties, based on VR and 2D viewing modes?*

- *Whether surface textures have an influence on the perceptual responses identified in those two viewing modes?*

- *How is the visual difference between VR and 2D reflected in the perceptual expression of materials?*

In the digital representation of opaque materials, the bidirectional reflection distribution function (BRDF) is often used for rendering surface appearances with varied reflectivity (Ngan *et al*., 2006). As a computational model, BRDF attempts to realise the display of material properties through simulating light-surface interactions. However, the material appearance depends not only on the computation of BRDF, but also human visual judgment (Adelson, 2001; Fleming, 2014). The human visual system is capable of neural coding of images and estimating the material properties of the object surface, such as gloss, texture, and shape (Beck & Prazdny, 1981; Todd *et al*., 2004; Motoyoshi *et al*., 2007; Sharan *et al*., 2008; Anderson & Kim, 2009; Marlow *et al*., 2011; Kim *et al*., 2011b, 2012, 2014). Furthermore, the appearance of materials also has a semantic effect, which can guide users' emotional changes. In summary, this study aims to investigate how the VR viewing mode may affect the users' perception of material visualisation, such as perception experience, material properties, as well as texture and emotional responses. To embark this research inquiry, four research hypotheses were formulated:

> *$H1_a$: There are differences in material perception between VR and traditional 2D viewing modes;*
>
> *$H2_a$: The user's perceptual response to material properties conforms to psychophysical law under VR and 2D viewing modes;*
>
> *$H3_a$: The texture attributes of materials influence how users perceive materials in VR and traditional 2D viewing modes;*
>
> *$H4_a$: The users' emotional responses of materials are affected in VR and traditional 2D viewing modes.*

### Section 1.2.3 Originality of the Research

As a method to measure the usability of the designed content, design evaluation has the ability to effectively and quickly detect defects in the design practice (Toma *et al*., 2012). In fact, before putting the concept into production, designers must constantly adjust and update the design scheme to avoid wasted efforts in the production process. As Gomes de Sá and Zachmann (1999) stated, the early design stage will affect 70% of the total production cost of the product.

As the previous application statement, VR is committed to creating a scenario that approaches the real world in design evaluation. However, for the material visualisation of the design field, users' material perception brought by VR visual effects has not been clearly explained. This study attempts to supplement this part.

Based on this, the contributions of the research are summarised as follows:

- *Validated the difference between users' perception of materials in VR and traditional 2D viewing modes;*

The originality of this research is mainly due to the positioning. In the current research focusing on material perception, VR, as a display device, is responsible for presenting the visual effects of materials. By grouping material perception research with viewing modes in virtual environments, this thesis has undertaken an investigation on users' perceptual feeling between different devices.

- *Derived the perceptual scale for VR viewing mode by psychophysics;*

This thesis has carried out research that establishes the users' perceptual scale for identifying material properties. Psychophysics method helps to establish the effective perceptual scales. Immersive viewing mode has changed both the design activities and the evaluation modes. The perceptual scale also provides an important sight for designing the interface for material properties manipulation in 3D software.

- *Confirmed users could perceive more material information under the VR viewing mode;*

An original aspect of the researched work is to take the user's identification and judgment of material properties as the influencing factor of perceptual material visualisation. The immersive VR viewing mode provides users with a free interaction to make judgments. This contributes to the users or designers evaluating material properties and integrating the perceived results into subsequent development.

- *Reviewed the perceptual effect of material attributes based on texture mapping through VR and traditional 2D viewing modes;*

This study points out that texture mapping affects users' identification of material properties. Through the research on the comparison of perceptual scales with and without texture materials, texture mapping has a negative impact on visual information. This research point bridged the research gap of texture mapping and material roughness response in the virtual environment.

- *Analysed the users' embodied cognition on the perceptual effect of materials in VR and traditional 2D viewing modes.*

This research takes two viewing modes as an expression carrier for emotional design and explores the relationship between user emotional response and material perception. This helps designers to express their intentions to the users through reasonable material expression.

## Section 1.3 Thesis Structure

The previous sections have completed the discussion of design significance by material visualisation. From the design perspective, only by accurately expressing the material appearances can designers obtain consumers' demand for products (Wei *et al.*, 2011; Yang, 2011). The research framework of this thesis adopts the three stages of material perception in the visual system submitted by Fleming (2017), as shown in Figure 1.3, to answer the research questions proposed:

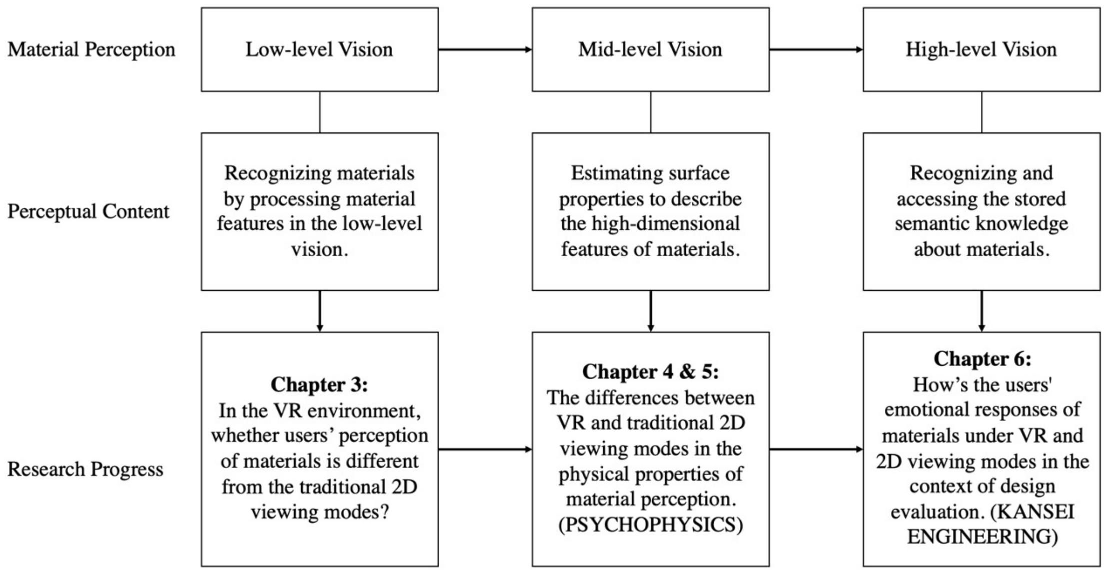


*Figure 1.3. Research Structure of the Thesis.*

The rest of the thesis is structured as follows:

Chapter 2 covers the theoretical framework of this study through the discussion of related content to construct the starting point of the research method. Firstly, the research background is based on material visualisation. The thesis gives an overview of the research in this field and explain how the current study can digitally express materials, such as computational models (BRDF) and visual perception of material properties. Subsequently, because visual perception affects the judgment of material properties, this chapter summarises the research on material perception and perceptual evaluation in visual content. This chapter mainly discusses the influence of VR technology on material perception and the standard evaluation methods of material perception at this stage. Next, the chapter reviews the current research on display mode and development in CAD and VR technology. The chapter also gives an overview of VR display and content generation. Finally, this chapter also summarises the research gaps in the field of material perception in the VR environment and points out the research contributions of this thesis.

Chapter 3 presents an initial study that evaluate the users' responses towards the visualisation of varied materials under VR and 2D viewing modes. This helps us validate firstly whether there is any perceptual difference of material appearances in VR and traditional 2D viewing modes. Based on the users' responses, the study has validated that VR and traditional 2D viewing modes can invoke different perceptual responses of the users. This finding supports the feasibility of subsequent research and analysis of the perceived difference between the two viewing modes.

In the next step, this thesis focuses on the difference between VR and traditional 2D viewing modes in the physical properties of material perception. The thesis validates and quantify the performance of this difference in detail concerning the aspects of material perception.

Chapter 4 focuses on the users' recognition ability of material properties under VR and traditional 2D viewing mode. Based on the psychophysical method, the research established the perceptual scale for material properties and used it as a visual stimulus for user testing. This study used metal and plastic without texture mapping as test materials. Through the users' visual matching task of material attributes, the thesis conclude that the VR environment can support users to accurately and precisely judge material attribute information.

Chapter 5 compares the changes in material properties that users can accurately perceive in VR and 2D viewing modes, taking roughness as a test example. This chapter considers the visual image effect of texture mapping on material perception.

Similarly, the experiment is based on the psychophysics approach to analyse the changes that users can perceive. This study has found that the texture has influences on the users' judgment on the change of material properties (roughness). In addition, the participants perceive more detailed changes in material properties under VR viewing mode. These results also support the idea that VR provides a viewing environment for more accurate material judgment.

Chapter 6 focuses on the users' emotional responses of materials under VR and 2D viewing modes in the context of design evaluation. This research has adopted the Kansei Engineering (KE) approach (Nagamachi, 1995) to analyse the affective connotations of materials, in particular their differences in VR and 2D viewing modes. At first, the research has elicited the semantic scales for measuring the users' emotional responses. The immersive VR and non-immersive 2D visual modes are then used to present the materials and obtain the participants' responses. Seven common material types were selected for comparative testing. In these tests, semantic evaluation is embodied as the process of perceptual expression and meaning construction of materials. According to the analysis results, it is concluded that VR is more suitable for highlighting the affective meaning of materials linked to apparent textures or visual details. At the same time, the 2D viewing mode works more effectively in the semantic expression of materials that emphasise plain features such as colours.

Chapter 7 combines all the findings and insights in the previous chapters and discuss them in response to the research questions. The tool selection and design criteria for material expression for design evaluation are proposed. The study results in this thesis will help explore further the development and use of VR for visual analysis of material perception. In addition, by reviewing the limitations of this research, the direction and inspiration for future research are also summarised.

# Chapter 2 Literature Review

## Section 2.1 Introduction

Visual perception can help us understand the cues of the surrounding environment, such as material properties. At the same time, the obtained visual cues are used to repeatedly evaluate and change the design content to ensure the smooth progress of the subsequent production and development process. This is inseparable from supporting existing knowledge in different fields, such as material simulation, demonstration tools, design standards, interdisciplinary research interacts with material perception, and design evaluation. The introduction of VR technology into the design evaluation process creates a user-friendly immersive visual environment in the field of modern product design. In particular, the immersive environment stimulates the users' internal experience and sense of presence, so the design optimization measures become easy to implement.

This chapter summarises the systematic review of current research on material visualisation and material perception. In addition, the thesis summarises the application of presentation tools as the inspiration and starting point for follow-up research. In the following sections, this thesis discusses in detail the academic research related to the research background mentioned above, as shown in Figure 2.1:

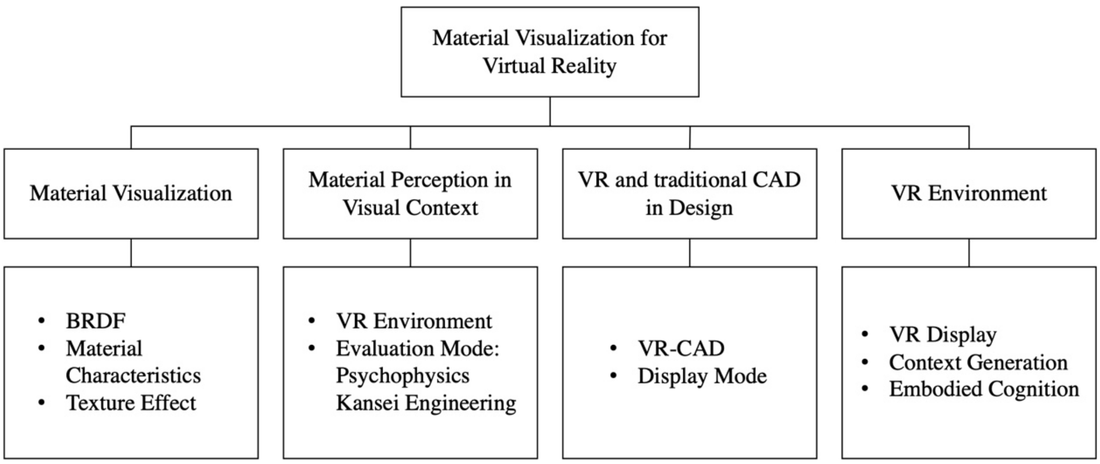


*Figure 2.1. Research Outline.*

Material Visualisation: the simulated material appearance is the essential content of design evaluation. In addition, visual perception acts on identifying material properties.

Designers must consider material properties, such as colour, texture, and optical properties, to accurately simulate material appearance. These simulations are often utilized for the user to perceive and evaluate the material properties and characteristics. Therefore, this section reviews the research on the material computing model, which helps deepen the understanding of material visualisation.

Material Perception in Visual Context: material perception is the outcome of a multi-sensory combination in the design evaluation. Specifically, this section focuses on existing material perception in a visual context and reviews the research on material perception in a VR environment. Similarly, since the results of material perception need to be evaluated, this section also summarises two commonly evaluated methods of material perception, namely, the exploration of visual perception in psychophysics (for material physical attributes) and Kansei Engineering (for material perceptual semantics).

VR and CAD in Design: design tools are the basis of performing the evaluation. From the perspective of current design tools, VR and CAD display devices for generating and realizing design content. VR-CAD is an application that operates virtual prototyping (or realizes interactive effect) in an immersive VR environment. Therefore, this section discusses the display mode and technology development of VR-CAD and traditional CAD software. This section explores and summarises the performance of two different viewing modes in design and application.

VR Environment: the implementation of VR-CAD technology is based on the development and improvement of VR devices. This section briefly summarises the research status on the development of VR devices and the generation of digital context in an immersive visual environment. Also, the embodied cognition in VR environment is worthy for reviewing.

## Section 2.2 Material Visualisation

The significance of material visualisation is to help users observe materials in digital form. People can estimate and classify the relevant characteristics of synthesised materials and obtain material information through vision (Binns, 1937; Adelson, 2001; Tiest & Kappers, 2007; Anderson, 2011; Zaidi, 2011). Material visualisation provides reliable technical support for the follow-up study on identifying and perceiving materials by simulating and rendering the material appearances.

The simulation of material property effect also determines the perceived quality of users. One of the important elements of rendered materials is the surface reflection models (Pessoa *et al*., 2010). In 3D computer graphics, opaque materials are represented as BRDF (Raymond *et al*., 2016). As a result, much work has aimed at exploring and understanding how BRDF evaluates and influences material properties. In BRDF-based materials, roughness and specularity are the two major parameters that modulate the rendering outcome. Modern rendering systems usually provide BRDF editing functions. Pellacini *et al*. (2000) observed that because the perceptual change of material appearance was nonlinear by nature, the adjustment of BRDF parameters might result in an uncertain rendering outcome. Other work focused on the feedback of BRDF editing to ensure that appearances and lighting could be handled at the same time (Sun *et al*., 2007; Cheslack-Postava *et al*., 2008; Nguyen *et al*., 2010; Serrano *et al*., 2018). Indeed, physical objects and its illumination properties still need to go through the necessary perceptual process for constructing a meaningful representation. And that process starts with the retinal images that reflect light from the shape and surface of the object (Marlow *et al*., 2012). Several existing researches in vision science studied object shapes based on the surface materials, as well as the human visual characteristics related to material properties. Nishida & Shinya (1998) found that the participants could judge the specular reflection of the smooth surface simulated by the computer, and the constancy of glossiness could not be guaranteed when the geometry was changed. Fleming *et al*. (2003) showed that the human visual system relied on real-world lighting conditions to more accurately judge the characteristics of materials, in particular the reflected specularity. Berzhanskaya *et al*. (2005) then studied how glossiness propagated from highlights on the surface of three-dimensional objects. In terms of roughness, Ho *et al*. (2006) studied how scene illumination and observer viewpoint affected texture perception. Doerschner *et al*. (2010) used scaling techniques to investigate the perception of roughness. There are also many studies on the influence of external factors such as illumination on material perception (Leung & Malik, 2001; Vangorp *et al*., 2017; Lagunas *et al*., 2019).

IJsselsteijn *et al*. (1998) found that the increase in depth could enhance the sense of presence on the premise that the perception of depth must be natural. Several research works have studied the perceptual differences between real images and synthetic images generated by rendering algorithms (Meyer *et al*., 1986; Drago & Myszkowski, 2001; McNamara, 2006; Vangorp *et al*., 2014). These previous works calibrated the parameters of rendering methods and the display devices but did not produce a comparative exploration related to binocular projection and its resulted depth impression. Hu *et al*. (2000) found that once the shadow effect was added, the ability to judge the contact between objects in virtual reality could be improved. The addition of tactile feedback was found to be constructive to the judgment of depth perception (Bouguila *et al*., 2000; Swapp *et al*., 2006). VR has been known for its depth effects and is used as a versatile tool in the design field (Nathanael *et al*., 2016; Rhiu *et al*., 2020). Due to the expensive and time-consuming characteristics of the physical model, VR could be utilized as a visualisation and evaluation tool at the early stage of the development process. (Mujber *et al*., 2004). Passig (2009) argued that users in a virtual environment would be more actively involved in the designated tasks. The argument is consistent with the view that VR improves various task performances (Slater *et al*., 1996; Laha & Bowman, 2012; da Costa & Nedel, 2017). Laha & Bowman (2012) discussed the positive impact brought by a virtual environment on forming stereoscopic and wide field of views, despite there were still differences between VR and reality. This was also confirmed by other related studies (Cummings & Bailenson, 2016). To sum up, many researchers explored the depth effect in VR and compared it with a 2D viewing mode. However, the research on material visualisation in VR is still fairly limited.

### Section 2.2.1 BRDF

When light strikes the surface of an object, a series of visual changes will occur in the material appearance, such as reflection, projection, or absorption. The Bidirectional Reflection Distribution Function (BRDF) describes the reflection of varied incident light on the surface of opaque materials (Nicodemus, 1965, Nicodemus *et al*., 1997). As a term, "bidirectional" defines the relationship between the exact direction of incident light and reflected light. In addition, BRDF measures the proportion of reflected light in each direction as a calculation function and provides the mathematical reflection characteristics of light acting on the material surface. Ha & Woo (2010) evaluated the fitting and measurement quality of several well-known BRDF analysis models. The authors recognized that these physical optics-based analytical models simulate most isotropic materials' appearance.

Designers are required to effectively capture the relationship between light and surface materials to determine the rendering effect of the object's surface in the graphics system (Anderson, 2011). In fact, designers can simulate approximate materials by analysing the material parameters in the image (Cook & Torrence, 1982; Ward, 1992; Lafortune *et al*., 1997; Ashikhmin & Shirley, 2000; Ngan *et al*., 2005, 2006). Hence, how accurately drawing the reflection effect is a long-term challenge in the field of imaging. BRDF contains a variety of analysis models. Many studies tried to optimize the application scope of the BRDF calculation model so that the function can conduct more realistic material visualisation. For example, the research of Barla *et al*. (2018) introduced the rendering of materials that exhibit hazy reflections and maps visual perception parameters to the physical parameters of materials. Xu *et al*. (2014) proposed to render the mutual reflection effect of total frequency BRDF of various materials. Ignatenko *et al*. (2004) described a general BRDF with a unique algorithm based on real-time reflection texture. Besides that, some research focused on simplifying the BRDF model and realizing efficient rendering. Raymond *et al*. (2016) concentrated on the multi-scale rendering of scratched materials and introduced a spatially varying BRDF model. Some previous work also put forward similar ideas (Dupuy *et al*., 2013; Jakob *et al*., 2014; Dong *et al*., 2015).

However, understanding these models and algorithms may seem complex to the designer. In order to enable designers to make better use of the professional knowledge of material specifications, Westlund & Meyer (2001) established the corresponding relationship between the measurement scale and BRDF model parameters according to the formulation standard of material appearance. Ngan *et al*. (2006) provided an intuitive visual interface for BRDF parameter specification, which is convenient for designers to select material parameters directly. Inspired by Pellacini *et al.* (2000), this study explored the users' perceptual differences of gloss materials based on BRDF rendered image description from a psychophysical perspective. The update of the BRDF algorithm standardizes the surface reflectance (Lucht *et al.*, 2000) in light source direction and spatial environment and also provides a fundamental guarantee for the subsequent rendering software to simulate materials.

### Section 2.2.2 Material Characteristics

The visual system can separate the material information and cues recognized from the environment in the early stage of retinal image processing. Chadwick & Kentridge (2015) emphasised that almost visual exploration needs to consider the complex interaction between lighting, material surface reflection, and observers. Because some material properties perceived are always related to the reflection of light. The angle of light acts on the surface materials to form complex image structures in the visual expression of materials and supports people in recognizing these material features.

The initial research, taking glossiness as an example, tried to find a method to measure the physical glossiness of surface materials. Based on the research of Hunter (1937), a gloss meter was developed to measure the specular and diffuse reflectance ratios in subsequent industrial tests. Although, many scholars indicated that the visual system does not estimate the physical quantity of a single gloss, and the visual judgment of gloss regards multiple dimensions and features in the image as a whole (Sève, 1993; Obein *et al.*, 2004; Chadwick & Kentridge, 2015; Mao *et al.*, 2019; Lagunas *et al.*, 2021). Marlow *et al.* (2012) put forward a view that our visual system is not aimed at evaluating the physical properties of surface materials. Our brain will measure the functional, statistical patterns or cues that can be recognized according to the visual image. The author's view means that the gloss perception depends on the ability of the human visual system to encode the edge structure of specular reflection. In this regard, Kim *et al.* (2016) agreed with Marlow's view and stressed that the gloss recognized by people visually depends on the structure of brightness change in the image. Sakano & Ando (2010) found that binocular parallax can improve gloss perception. Wendt *et al.* (2010) also showed that parallax could improve the stability of gloss matching when the object shape changes.

The specular reflection on the surface object will also affect the users' judgment of material roughness. Some later studies believed that our recognition of material properties does not rely on the surface parameters (Geisler, 2008; Fleming, 2014). The visual system statistically describes the material characteristics (Giesel & Zaidi, 2013) and textures (Julez, 1962; Schafalitzky & Zisserman, 2001). Ho *et al.* (2006, 2007) explained that the observers evaluate the surface roughness according to the proportion of shadow pixels in the image. Motoyoshi *et al.* (2007) also published a similar conclusion: the distribution inclination of brightness value is related to the effect of surface gloss.

In addition, a research area of graphics is the evaluation of visual effects that affect the material properties in lighting environments (Beck & Prazdny, 1981; Bousseau *et al.*, 2011; Zhang *et al.*, 2015; Faul, 2019). Berzhanskaya *et al.* (2005) measured the glossiness of highlight propagation from the 3D object surface. Fleming *et al.* (2003) compared the asymmetric matching performance of material stimuli under a real-world lighting environment. There are some controversial discussions in this area. Doerschner *et al.* (2010) indicated that the evaluation method of symmetric matching could keep the participants' gloss perception consistent. Recent research explores how people's visual system encodes visual images effectively and accurately (Bell *et al.*, 2015; Wang *et al.*, 2016, Lagunas *et al.*, 2019; Fleming & Storrs, 2019). These studies supplement the information perceived by the material visualisation and simulation in the human visual system.

### Section 2.2.3 Texture Effect

Material perception is a perceptual mode combined with sensory stimuli. People can distinguish different materials depending on the different visual characteristics of these materials in retinal images. These visual features constitute the reflected light patterns on the material surface so that people can identify different material properties (Fleming *et al.*, 2003; Ho *et al.*, 2006; Marlow *et al.*, 2012; Komatsu & Goda, 2018). Ho *et al.* (2006) examined how roughness perception is affected by scene illumination and observer viewpoint. Emrith *et al.* (2010) research on roughness perception is based on the scale method (Maloney & Brainard, 2010). Goodman (2012) explored the relationship between materials' perceptual and physical properties. Nishida (2019) found that the decrease in brightness and contrast will increase a human's ability to recognize texture. Gigilashvili *et al.* (2019) assumed that colour and translucency degree also affect users' perception of gloss. Similarly, Honson *et al.* (2020) considered the difference between specular reflection and diffuse reflection on the gloss of surface materials, which mainly depends on how the human visual system distinguishes potential optical reflections in the image. However, these perceptual effects are also related to the 3D layout of surface materials (Kim *et al.*, 2011b; Marlow *et al.*, 2015).

In real world, physical materials usually exhibit another important feature, surface textures, which could contribute to the perceived outcome of material properties. Previous studies have discussed textural perception (Lederman & Klatzky, 2004; Hagh-Shenas *et al.*, 2006; Whitaker *et al.*, 2008) and texture evaluation (Mojsilovic et al., 2000; Filip *et al.*, 2011; Serrano *et al.*, 2018). Groissboeck *et al.* (2010) discussed a method that allows visual textures to be associated with given human perception. Yuen & Wünsche (2011) reviewed the different parameters that affect the appearance of fabrics, but this required high quality for rendering performance. Filip *et al.* (2008) compared the judgment difference between the users' material properties when observing the computer rendering effect and the actual material samples. Hepperle *et al.*, (2017) discussed how different physically existing materials can be mapped on virtual textures in Mixed Reality environments. The research on the judgment of material properties is mainly on recognising roughness (Domanski & Wolinski, 1992; Gunarathne & Christidis, 2000; Moslehpour *et al.*, 2008). These studies are based on visual and tactile perception. Wang *et al.* (2010) introduced a computer vision technology that can be used to measure fabric surface roughness. Mengoni *et al.*, (2011) combined both mechanical and electrotactile approaches to simulate natural tactile sensations on material properties. The authors integrated acoustic and visual cues to enhance experience. Cullbertson *et al.* (2014) proposed to create a tactile texture model in a natural interactive way to evaluate the authenticity of virtual texture and they discussed the advantages and disadvantages of this method. Hartcher-O'Brien *et al.* (2019) explored the perception of the roughness of 3D printing material samples. Degraen *et al.*, (2020) combined visual and haptic feedback to enhance the material experiences in VR. The authors found that overlaying materials with visual textures, the resolution of the user's haptic perception increased.

According to the above review, this section observed the following key insights from Material Visualisation:

(1) the visual simulation of opaque materials is realized by the computational model BRDF;

(2) some study expects to create a material simulation proposal by building a bridge between designers and calculation parameters so that designers can understand the visual expression of the BRDF algorithm;

(3) visual perception can help users to identify material properties;

(4) people encode images through the brain to identify material properties such as gloss and roughness;

(5) physical materials in real world exhibit unique textural effects, which could contribute to obtain essential information on material perception.

## Section 2.3 Material Perception in Virtual Context

Fleming (2017) summarised how the visual system perceives materials, as shown in Figure 2.1. The author claimed that the visual system processes some recognizable material features in the low-level vision through the captured image structure, texture, and other features. The visual system will estimate surface properties in the mid-level vision, such as gloss and transparency of these materials, as well as the physical properties such as hardness and roughness. Therefore, at this stage, vision can provide the possibility to describe the high-dimensional features of materials by evaluating the surface properties of different materials. High-level vision can recognize and access the stored semantic knowledge about materials. It is a feedforward view of material perception. In short, material perception is not only to evaluate the physical and optical properties of materials but also to include the meaning of visual information.

Most of the research on material perception focuses on visual and tactile perception, both of which provide non-negligible support for the judgment of material information. Baumgartner *et al*. (2013) found that the judgment results of material properties based on visual and tactile perception are quite similar, but vision provides better accuracy in performing material classification tasks (Baumgartner *et al*., 2015). Humans can recognize materials by observing photos and even simply judge the physical properties of materials (Sharan *et al*., 2008, 2009; Maloney & Brainard, 2010; Fleming *et al*., 2013, 2015; Jarabo *et al*., 2014; Nagai *et al*., 2015; Serrano *et al*., 2018). For example, Nagai *et al*. (2015) tested users' response time to the relationship between material surface features and material categories in material images. The authors thought that the optical surface features of materials are sufficient to explain people's recognition of materials. Other researchers stated that humans could identify materials by visual features because this material information matches the input data of our visual system (Adelson, 2000; Motoyoshi *et al*., 2007; Thompston *et al*., 2016).

Therefore, the surface characteristics of materials provide the visual cues required for material perception. However, the process of material perception is complex because many variables are involved in the evaluation stage (Anderson 2011; Fleming 2014). Much work is devoted to analysing the relationship between materials and surface characteristics. Giesel & Zaidi (2013) proposed a perceptual mechanism to identify material properties, taking fabric as an example. In this research, the 3D surface characteristics are estimated by the 2D frequency representation of the material image. Bell *et al*. (2015) used an extensive annotated database to identify local materials. Schwartz & Nishino (2016) introduced global contextual cues. Meanwhile, Fleming (2017) proposed a classification technology based on material characteristics, enriching real-world materials' subjective experience. Zhang *et al*. (2018) used perceived deep features to evaluate the similarity between the two images of the test materials. In the latest research, Lagunas *et al*. (2019) proposed a model to measure the appearance similarity between different materials and pointed out that this is related to the judgment of human perceived similarity. Moreover, these material comparisons are based on measuring material properties in image space (Ngan *et al*., 2005, 2006; Fores *et al*., 2012; Pereira & Rusinkiewicz, 2012; Sun *et al*., 2017) or calculating material parameters to analyse the human perceptual properties (Pellacini *et al*., 2000; Serrano *et al*., 2018). In addition to material classification, many computer graphics studies focus on exploring single properties of materials. For example, the application of editing and processing of synthesized surface materials (Jarabo *et al*., 2014; Mylo *et al*., 2017; Zsolnai-Feher *et al*., 2018), and gloss perception are mentioned in Section 2.2.

### Section 2.3.1 Material Perception in VR Viewing Mode

Binocular parallax is considered the source of perceived gloss information (Sève, 1993; Obein *et al*., 2004; Chadwick & Kentridge, 2015). This is because the specular reflection presents the effect of opposite reflection angles with the same illuminant, and each eye receives information concerning the position of the highlight on the surface differently. Therefore, this visual difference makes people feel more distinct material properties (Wendt *et al*., 2008; Formankiewicz & Mollon, 2009; Chadwick & Kentridge, 2015). On the contrary, it also means that evaluating materials in a viewing mode with a lack of parallax may affect the estimation of material properties. According to earlier research, Methven & Chantler (2012) made more natural rendering operations of test objects and surface materials, and they found that adding different information to specular highlights would enhance the perceptual effect of gloss. Muryy *et al*. (2013) also recognized the significance of binocular parallax on the perception of material properties. The author pointed out that the brain's interpretation of specular objects does not rely on the principle of physical reflection. Similarly, Kerrigan & Adams (2013) provided a similar view. The authors tested the effect of binocular parallax to recognize the curvature (convex or concave) of the object's surface. The results showed that binocular parallax could help participants distinguish between specular highlights and changes in object surface height. Recognizing this visual effect also helps people correctly classify and judge the roughness level of materials (Fleming & Bülthoff, 2005; Ged *et al*., 2010; Li & Fritz, 2012; Fleming, 2014). So, the shape of surface materials determines what they look like and what information or results people can perceive (Nishida & Shinya, 1998; Vangorp *et al*., 2007; Olkkonen & Brainard, 2011; Havran *et al*., 2016; Schlüter & Faul, 2019).

VR is mainly used in product design, architecture, and engineering (Lorenz *et al*., 2016; Zaker & Coloma, 2018; Asadzadeh *et al*., 2020) and often exists as a design review tool (Wang, 2002; Berg & Vance, 2017; Kassem *et al*., 2017; Gong *et al*., 2019; Balzerkiewitz & Stechert, 2020). As early as 1999, De SA & Zachman (1999) proposed using VR in design evaluation. In the follow-up study, Naef & Payne (2007) developed a VR tool to operate 3D models. Unlike the previous CAD operation mode, VR saves project cost and time. In addition, Cecil & Kanchanapiboon (2007) and Cambrun *et al*. (2017) also support this view. However, it is still controversial whether VR technology can provide more realistic interaction and experience effects, but most studies recognise the significance of VR as a participatory design tool (Wolfartsberger, 2019). In our daily life, people are good at perceiving the mechanical properties (such as stiffness) and optical properties (such as surface gloss) of materials attached to the product surface (Adelson, 2001; Sharan *et al*., 2014; Bi & Xiao, 2016). Many studies established models to connect user perception with material representation. Kim *et al*. (2006) designed a system that can be applied to textile index and matched textile images for classification. Meanwhile, the influence of design parameters such as material, colour, and brightness were evaluated by Naz *et al*. (2017) on the space by simulating the design attributes in the virtual space. Naylor *et al*., (2020) demonstrated how our past experience with material and weight can create expectations that influence the material-weight illusion of an object in VR environment. Niu & Lo (2022) assessed the visual judgment ability of VR on material perception.

VR's HMD achieves the binocular parallax by delivering different image frames via the left and right lenses. Scarfe & Glennerster (2015) found that the perception research tested in VR is to study human perception by exploring highly real stimuli in a controllable way. Based on this, the visual effect in a VR environment is often combined with the research of material evaluation. Kuliga *et al.* (2015) and Heydarian *et al.* (2015) verified the positive effect of VR environment on physical environment experience. This is beneficial to the design inspection work, which requires an operation and modification process (Bruggeman *et al.*, 2007; Jain & Backus, 2010). Ohkura *et al.* (2019) applied VR technology to the colour evaluation of the packaging design. After that, Gökmenoğlu & Akbay (2021) also explored the influence of colour perception on an immersion experience in the virtual environment. The authors estimated the hue, saturation, and brightness of colour, and suggested that designers appropriately reduce colour luminance or increase the brightness to improve the immersion feeling. However, this kind of conclusion of the studies proposed is based on a non-immersive virtual environment (desktop mode of virtual environment). Zhang *et al.* (2019) considered the material impact of interior decoration on the living environment in daily life, so a visual evaluation environment is designed to enable users to select materials according to their visual aesthetic preferences. This interactive method in this study based on Immersive Virtual Reality (IVR) is adopted. Malpica *et al.*, (2020) studied the influence of sound on visual perception in a virtual reality scenario. Unfortunately, in the research of VR applied to design evaluation, materials play a role in assisting the design effect and have not received sufficient attention. However, binocular parallax has such a meaningful impact on material perception.

### Section 2.3.2 Material Perception Evaluation Mode

From the designers' perspective, the evaluation of material perception often needs to establish the corresponding relationship with the design results (Karana *et al.*, 2008; 2010). Pallasmaa (2012) pointed out that vision can reveal the predicted tactile experience of materials. Meanwhile, users can perceive the physical properties of materials through visual evaluation. Designers usually need to consider the correlation between rendered materials and actual material properties (Tiest & Kappers, 2006; Wongsriruksa *et al.*, 2012; Klöcker *et al.*, 2013; Shin *et al.*, 2020).

#### *Psychophysics Approach*

Psychophysics tests the viewer’s ability to recognize and differentiate stimuli. Its core element is the sensory threshold, which can measure the acute sensitivity of an external stimulus. The difference threshold is termed as the Just Noticeable Differences (JND) in human sensation. The authors proposed a reflection model of material surface gloss based on a psychophysics approach. Initial psychophysics studies have revealed that a linear relationship is not enough to describe the relationship between the perceptual and physical dimensions, although it can be related (Doerschner et al., 2010). For example, Obein et al. (2004) found no linear distribution between the gloss perceived by the observers and the gloss value measured by the instrument. The scholars tried to summarise these nonlinear relationships to explain these perceptible changes - Just Noticeable Difference (JND). These JNDs often follow specific rules, such as Weber's law. In other words, these rules mean that the perceptual correlation is predictable (Rensink, 2017; Whitney et al., 2018).

Furthermore, psychophysics provides testing methods to define the perceptual scale's structure specifically. These methods determine how stimulus levels respond to different test forms. The most common methods are Method of Limits (MoL), Method of Adjustment (MoA), and Method of Constant Stimulus (MoCS). Among them, the Method of Limits is suitable for observing the value of a single variable, the Method of Adjustment allows for labelling and adjusting stimuli and also detecting scales within continuous levels (Bartram & Stone, 2011), and the Method of Constant Stimulus supports the detection of absolute threshold and the identification of relative threshold and stimulus classification (Gleicher *et al*., 2013). When applying psychophysics to the practical test research, Ho *et al*. (2006) found that the angle of the illuminant is related to the perception of roughness. Cunningham *et al*. (2007) studied the relationship between transparency and material gloss. Meanwhile, Bouman *et al*. (2013) considered the human ability to estimate fabric stiffness and density in the dynamic video. Martin *et al*. (2015) quantified visual and auditory stimuli's single and comprehensive effects on material properties through two psychophysical experiments. These finding also refers to the research of Adelson (2001), Maloney & Brainard (2010), and Fleming (2014) and give an overview description. In brief, psychophysics is the evaluation method of material perception with strict requirements for experimental implementation but also provides data application to support subsequent design activities and development.

Visualisation techniques help us explore, observe, and analyse a set of data through human perceptual and cognitive abilities. Psychophysical methods can be used to evaluate the visual perception and provide empirical guidance for design (Elliott, 2021), e.g., eliciting consumers' perceptual responses to product features. For example, several earlier studies have shown that the presentation of visual features served as a mean to induce perceptual differences in design customization (Montello, 2002; Ware 2010; Roth, 2012; Zacks & Franconeri, 2020). Other researchers also used visual psychophysics to explore the control and effects of stimuli in a modelled system (Reise *et al*., 2005; RichardWebster *et al*., 2018). Most of these studies are aimed at developing computer vision-based solutions with algorithmic optimizations in visual processing. The use of these perceptual methods has been well documented in the relevant visualisation studies (Brewer et al., 2003; Harrison et al., 2014; Beecham et al., 2017; Szafir, 2017; Elliott, 2021). Indeed, the shape of the object's surface, such as the degree of curvature, be perceived differently due to varied lighting conditions (Mingolla & Todd, 1986; Todd et al., 1997; Nefs et al. 2006), which affect the perceived reflectivity of surfaces (Nishida & Shinya, 1998; Norman et al., 2004). Ferwerda et al. (2001) research aims to solve the relationship between the material perceptual and physical dimensions. There exist more specific studies in design such as Nie *et al*. (2019), which combined psychophysics and environmental preference theory to evaluate and analyse a certain number of tourism buildings, to identify the factors affecting user preferences and put forward guidelines for future design. Sousa *et al*. (2020) investigated the influence of colour and shape of packaging label design elements on the sensory and hedonic judgment of specialty coffee by non-professional consumers. Deng & Wang (2020) applied the analysis methods of Kansei engineering to extract the aesthetic perception factors of users on the human-computer interaction interface and construct the aesthetic evaluation model.

The design goal is a series of activities centred on users and determining the direction and process of design by users' feelings. Therefore, many studies tried to quantify users' abstract "consciousness" and reflect the design idea from digital expression. These studies used visual features as a means to measure perceptual differences to simulate and adjust the control of stimuli in the trial (Reise *et al*., 2005; RichardWebster *et al*., 2018). Yohanan & MacLean (2011) designed an "emotional" model that adjusts the emotion of users when interacting with devices. Based on psychophysics, Israr & Poupyrev (2011) developed a model to control and regulate motion perception on human skin. In addition, to emphasise the role of visual perception in design evaluation, psychophysical research has also been applied to architectural design (Nie *et al*., 2019), product design (Deng & Wang, 2020), and packaging design (de Sousa *et al*., 2020). Wongsriruksa *et al*. (2012) reviewed the application of the VR environment in visual psychology research. Psychophysics guides researchers to construct a response curve composed of the correlated results of a single stimulus and to determine the exact response value that subjects can identify the stimulus, rather than using aggregate statistics to measure performance. In these studies, JND has proved its significance in visualisation research (Ekman, 1959; Harrison *et al*., 2014; Beecham *et al*., 2016; Szafir, 2017) and the development of 3D models (Brewer *et al*., 2003; Smart *et al*., 2019). So far, psychophysical methods have been devoted to exploring materials' surface characteristics and shape, especially in the measurement model of roughness (Lawson *et al*., 2003; Padilla *et al*., 2008; Ho *et al*., 2008). However, this kind of research focused more on tactile perception because it is considered a more intuitive expression of perception response (Murray *et al*., 2003; Gescheider, 2013). Ostrovsky *et al*. (2005) pointed out that the lighting effects detected on the surface of irregular geometric objects are inconsistent. Filip *et al*. (2008) showed through psychophysical research that the amount of data required to represent a material within a given perceived fidelity range depends on the characteristics of the material. Krohn *et al*. (2020) proposed an evaluation framework to help evaluate the experimental paradigm of Virtual Reality.

Psychophysics approaches have also been applied in the field of VR research. VR is advantageous in providing an unprecedented sense of presence to the users (Hvass *et al*., 2017). These studies mostly focused on 3D depth information, interactive mechanisms, or tactile feedback (Murray *et al*., 2003; Gescheider, 2013). Peillard *et al*. (2019) evaluated whether the participants' egocentric perception of the distance of the virtual target on the side was different from that of the object in front in the VR environment. Thaler *et al*. (2018) used the psychophysical framework to evaluate the perception of the "weight" of self-avatars in VR. The study showed that there was no gender difference in the accuracy of judging physical features. However, when comparing emotional or aesthetic judgments, gender factors are worth considering. Jo *et al*. (2019) determined the performance standard of wearable hand devices in VR through psychophysical evaluation and subjective experience analysis. Different from the monocular depth cues provided by the traditional 2D viewing mode, the stereoscopic depth cue provided by VR is constituted with visual information coming from two viewing perspectives (El Jamiy & Marsh, 2019). The two views correspond to the retinal images of the left eye and the right eye. Gourishetti & Manivannan (2019) found that the perception of force in immersive VR (IVR) was improved in comparison with non-immersive VR (NIVR, panoramic imagery on a 2D screen). They considered that this difference might be caused by the head-mounted display providing a 3D immersive view to the participants. Horiuchi *et al.* (2017) also indicated that when using 2D dis-play mode alone, the amplitude span of visual stimulation in the central visual field was greater than that in the peripheral visual field. The authors articulated that the improved JND performance might be relevant to the visual noise in the NIVR experiment, which was mostly eliminated in the IVR experiment. These studies show the usefulness and applicability in using psychophysical approaches to derive more objective and quantifiable findings on the perceptual issues in VR.

### *Kansei Engineering Approach*

Kansei Engineering is dedicated to expounding consumers' product preferences (Lai *et al.*, 2005; Hong *et al.*, 2008; Bahn *et al.*, 2009; Lin & Wei, 2014; Shen *et al.*, 2015) and feeding back to product design evaluation according to preference trends. As a design evaluation method, KE integrates the evaluation techniques of psychology, cognitive science, design, and computer science (Shiizuka, 2011). This approach is ordinarily divided into several methods, such as Type I, II, III, Hybrid, and Virtual, according to different evaluation items or data analysis (Nagamachi & LokMan, 2016). Besides, many studies try to update the KE method to engage in more design projects. For example, Schütte (2002) modified the general KE procedure, which is widely used in the study of food packaging, interior decoration and other design field (Schütte & Eklund, 2005; Dahlgaard *et al.*, 2008; Nordvik *et al.*, 2009; Schütte, 2013).

The emotional assessment correlates material parameters (or characteristics) and user perception. This evaluated mode requires exact perceptual evaluation criteria, like collected and selected Kansei words. In the field of Kansei Engineering, Kansei words are often determined by Multi-Dimensional Scaling (MDS) (Soufflet *et al.*, 2004) or semantic differential method (SD) (Kansei engineering as a tool). These Kansei words generally summarise users' impressions of products (Ersal *et al.*, 2011; Yang *et al.*, 2015; Yoon *et al.*, 2015). For instance, Karana *et al.* (2010) established a material meaning model to help designers discover the role of materials in design creation and expression. Chen *et al.* (2009) studied the relationship between the physical properties of packaging materials and tactile sensory judgment. Fenko *et al.* (2010) asked participants to describe the freshness of various materials only by vision. Wastiels *et al.* (2012) discussed the warmth of visual perception on wall materials in architecture.

At the same time, Kansei Engineering is also widely used to develop a satisfaction model based on material perception. You *et al.* (2006) designed a model to help designers choose design parameters and design features for automobile interiors. Mamaghani *et al.* (2014) determined the influencing factor between product features and perceptual words and formulated the design strategy for product appearance. Kim *et al.* (2018) focused on the visual perception of leather in automobile interiors, so the results inspired designers to generate preference and luxury models for those materials. A similar study was previously conducted by Ban *et al.* (2006). Despite the relatively extensive research on the emotional assessment of materials, the changing design industry still puts forward new requirements for the perceived content (Yumer *et al.*, 2015; Burnap *et al.*, 2016; Stylidis *et al.*, 2016; Ma *et al.*, 2017; Lin & Tseng, 2018). Therefore, the accurate prediction of material perception in product design is a topic of continuous exploration to balance the influencing factors such as existing technical support, development ability, and condition constraints.

When manufacturers consider the sensory impact on products, product functionality and appearance characteristics determine the focus of product development (Wright *et al.*, 2003; Liu, 2003; Rösler *et al.*, 2009). Therefore, previous studies believe designers should better integrate customer needs into product design (Bailetti & Litva, 1995; Chuang *et al.*, 2001). User-centred design is widely recognized (Szalma, 2009, 2014; Ho & Lu, 2014; Lo & Chu, 2014; Lo *et al.*, 2015; Qu & Guo, 2019), which largely depends on the design characteristics of the product (Hsiao & Ko, 2013; Chang & Chen, 2016, Guo *et al.*, 2020). The methods of KE (like Type I, Type II, Type III, Hybrid, and Virtual) are used to evaluate and analyse the data of users' perceptual experiences (Nagamachi & Lokman, 2015). Yan *et al.* (2008) proposed a model for perceptual evaluation, which can improve the strength of the evaluation system. Huang *et al*. (2011) designed a method for classifying perceptual attributes to measure customers' perceptual similarity between the meanings of Kansei words (KW). After that, Chou (2016) discussed the emotional evaluation based on word computing technology and verified its applicability. Coronado *et al*. (2021) systematically reviewed the application of KE as a design method for developing service robots. Due to the wide popularization of VR, it is also used to assist KE in user-centred research. For example, Huang *et al*. (2020) applied immersive VR technology to rehabilitate the upper limb, improving treatment satisfaction and effectiveness. Wu *et al*. (2020) explored a virtual learning system of design history on students' learning attitudes and obtained positive results. Edama *et al*. (2021) focused on using VR to visualise users' perceptual results. In the above studies, VR is more used as a presentation tool or media to explore design element by KE. Most of them is not discussed the emotional interaction between users and the VR environment, such as immersive effect and depth factors.

According to the above review, this section observed the following key insights from Material Perception in Visual Context:

(1) The visual perception process of materials visualisation is that the visual system in the primary stage recognizes the material characteristics and transfers them to the mid-level vision to evaluate them. After that, these characteristics are perceived by the high-level vision, and the relevant semantics are classified and evaluated;

(2) the appearance of surface materials provides visual cues for material perception;

(3) binocular parallax is conducive to the perception of material properties;

(4) psychophysics can quantify the visual perception of materials' properties;

(5) Kansei Engineering evaluates the correlation between material parameters and user preference.

## Section 2.4 VR and CAD in Design

### Section 2.4.1 VR-CAD Technological Development

The CAD software, in this thesis's context, refers to those offering shape/geometry modelling functions that are usually operated to give 3D forms of a product or its components. CAD software, such as Pro/E, SolidWorks, Creo, is used for generating 3D modelling and transfer to rendering engine to attach the material mapping for design evaluation. The application of VR technology to the design evaluation process relies on the digital model generation technology of CAD software. It provides technical support for user perceived materials. However, this kind of software highly depends on digital data input and requires users to operate the 3D models through a keyboard and mouse. The interaction mode of CAD software has not been changed or updated, although it is still practical and common. In the traditional 2D viewing mode, designers or users need to evaluate VP through the presentation of CAD software, and VP is projected onto the 2D electronic screen to convey visual effects. Kirpes *et al.* (2022) systematically reviewed the development process of the 3D product models. Some scholars noted that the 2D interface on CAD lacks natural interaction experience when processing the 3D virtual models (Song *et al.*, 2017; Yun & Leng, 2021). Early research has put forward some new attempts at CAD interactive mode. Dave *et al.* (2013) tried to enhance the user experience by attaching gestures in operating 3D objects and developing the way of traditional interactive workflow. Alibay *et al.* (2017) combined the multimodal input of gesture and voice commands into the CAD system (Feeman *et al.*, 2018). In addition, VR technology provides more possibilities for CAD interaction (Gomes de Sá & Zachmann, 1999; Biermann *et al.*, 2002; Lee *et al.*, 2004; Bourdot *et al.*, 2010). Researchers recognize the interactive advantages of VR technology, such as intuitively handling virtual prototyping and helping users get familiar with virtual environments.

The research on VR application in design evaluation has fully applied the multi-sensory nature of VR technology in user experience. Unlike the traditional 2D device that the design model can be displayed on, VR technology is compatible with the existing CAD platform and optimizes the presentation of output content (Friese *et al.*, 2008; Kosmadoudi *et al.*, 2013). Schnack *et al.* (2019) indicated that VR technology had the potential to surpass the traditional desktop applications in the field of telepresence with the induced sense of embodiment and immersion (Diemer *et al.*, 2015; Zielasko *et al.*, 2017). The interaction between VR and design experience provides the possibility to develop a more immersive visual experience. Some studies proved that VR interfaces produced better depth perception and viewing experience, henceforth improving the designer's intuitive understanding of a CAD model (Johansson & Ynnerman, 2004; Toma *et al.*, 2012; Satter & Butler, 2015; Berg & Vance 2017). For this reason, the VR system has a wide range of applications and performs well in collaborative design (Koutsabasis *et al.*, 2012; Nathanael *et al.*, 2016; Rhiu *et al.*, 2020; Mujber *et al.*, 2004), user experience evaluation (Rebelo *et al.*, 2012; Diemer *et al.*, 2015; Zielasko *et al.*, 2017) and architectural planning (Portman *et al.*, 2015).

Based on this, an emerging development focus is the VR-CAD integrated system that can operate and modify 3D virtual models in the VR environment (Dani & Gadh, 1997; Dellisanti *et al.*, 2007; Naumann *et al.*, 2007; Ingrassia & Gappello, 2009; Weidlich *et al.*, 2009; Bourdot *et al.*, 2010; Shen *et al.*, 2010). The primary developed VR-CAD system can only meet simple design activities such as sketching and is not enough to modify 3D models in the VR environment (Igarashi *et al.*, 1999; Fiorentino *et al.*, 2002; Keefe *et al.*, 2001, 2008; Ma & Gao, 2009). Such research focuses on Immersive surface modelling. For example, Fiorentino *et al.* (2002) designed software called 'Space Design,' which allows users to draw in a VR environment. Bordegoni *et al.* (2006b) and Owada *et al.* (2002) considered using tactile devices for the 3D model processing (Martin *et al.*, 2017). However, Toma *et al.* (2012) proposed that the interaction between designers or users and 3D objects requires two-way information exchange. VR system needs to establish an intuitive interaction mode between users and 3D models. Many studies have emphasised the requirements of immersive solid modelling (Trika *et al.*, 1997; Gao *et al.*, 2000; Ye *et al.*, 2006). In order to enable designers to process 3D models in an immersive virtual environment directly, Neugebauer *et al.* (2007) introduced a modelling system that allows users to interact with voice commands and gestures in VR and then compared it with a desktop system. The authors pointed out that the task completion rate in a VR environment is three times higher than in the traditional 2D viewing environment. Another standard VR-CAD development mode is Construction History Graphs (CHG), which are used to store the operating parameters or transition matrix of the CAD system and fully describe the design history of CAD objects. On this basis, Bourdot *et al.* (2010) proposed a VR-CAD framework for project review of collaborative part design, which can administrate the implicit editing of CAD objects. Meyrueis *et al.* (2009) stored the information in the pending CHG by the VR system and merged the modified model with the original 3D model in the CAD system. Wu *et al.* (2010) designed a system for the 3D part design, adding human-computer interaction speed, frequency, and time parameters to ergonomic evaluation. Furthermore, Kim *et al.* (2011a) developed a method of using virtual prototyping to analyse users' impressions of product design elements, which was applied to the case study of automobile interior design. Abidi *et al.* (2013) also conducted a similar study to evaluate the aesthetic and design characteristics of the 3D virtual prototyping for vehicle models.

In addition to editing the 3D models, VR-CAD is also applied to the virtual model assembly. Virtual prototyping is allowed assembly and disassembly relying on the natural interaction mode of VR technology (Qiu *et al*., 2013). Furthermore, this technology can widely support all kinds of professional training. Like, Borsci *et al.* (2015) demonstrated that trainees prefer the immersive vehicle maintenance training compared to the traditional desktop methods based on observation (Lawson *et al*., 2016). The continuous optimization of VR technology requires higher physical functions and technical support than the traditional desktop interaction mode. These studies believed that with the improvement of VR software and hardware development capabilities, VR technology could significantly reduce production costs and time and also avoid the waste of physical models (Fioretino *et al*., 2002; Kulkarni *et al*., 2011). Bustillo *et al.* (2015) designed a platform for creating a semi-immersive 3D environment suitable for generating 3D models with sufficient visual quality for teaching purposes. Fukuda *et al.* (2021) proposed a custom segmented rendering technology, which can calculate the linear velocity and angular velocity of each frame in the virtual camera under the VR space and superimpose colours on the screen according to the velocity value and apply it to urban design projects. Due to the immersive experience of the current VR system, designers can develop more realistic scenes and stimulate subjects' preferences through joint experiments. These studies clearly emphasised the significance of VR in the design of interactive experiences. However, from the perspective of human experience, VR is better defined as a "real or simulated environment" (Radianti *et al*., 2020). In this sense, the VR system is characterized by its perception of the virtual world and its physical existence in the virtual environment (Wloka, 1995). On the basis of human perception, VR technology put forward a new exploration demand for further research. Some studies discussed virtual objects' geometric and material properties in VR, such as texture (Zimmons & Panter, 2003), lighting, and reflection (Mania & Robinson, 2004; Slater *et al.*, 2009). The judgment of material perception is not only the visual optimization of the algorithm but also the review of the accuracy adjustment of tactile feedback equipment. Although more and more studies are devoted to developing convincing virtual scene simulation, it is unclear whether enhanced visual realism improves users' VR experience (Rizzo & Koenig, 2017; Pan & Hamilton, 2018; Slater *et al.*, 2020).

### Section 2.4.2 Display Mode

In the early stage, users refer to physical products to give their evaluated opinions. This method can get authentic feedback from users, but it has long been replaced due to time and cost consumption. Visual perception is the key to the whole interaction result for 3D model design and evaluation. According to different task requirements, the users' mental model based on the perceived information of the visual environment is different. The model visualisation projected on the 2D display mode lacks the experience of depth perception. So, the introduction of VR is to break this non-intuitive 2D display mode (Wang & Li, 2004; Rosenbaum, 2005). The modelling system based on VR technology makes designers no longer limited to the traditional 2D interface (Arangarasan & Gadh, 2000; Krause & Goble, 2004; Cavazza *et al.*, 2005), and can be widely used in product modelling design (Keefe, 2001; Leu *et al.*, 2001). Some studies have discussed the differences in user experience between 2D and immersive VR visual environments. For example, Sutcliffe & Deol Kaur (2008) compared the interaction modes of desktop VR systems and traditional 2D user interfaces. Saleeb (2015) showed that the perception in a VR environment differs from the real-world visual experience, even though the author only discussed geometry. In this kind of research, the perceptual colour difference is commonly investigated in visual research. Siess *et al.* (2018) compared the effects of colour parameters on user perception habits under the two display devices (HMD and computer screen). The authors found that visual output devices and participants' gender affect the significant differences in colour perception. Women tend to prefer cool colours in the VR environment. The author supplemented the research later and found that the users' operating time on the immersive VR devices will affect the subjective colour temperature preference. They indicated that compared with the traditional 2D viewing mode, VR with an HMD device provides a larger field of view and can display more test content in peripheral vision (Siess & Wölfel, 2019).

Previous studies have compared the impact of the display modes between the desktop devices and VR's HMD devices on the design activities, mainly focusing on comparing 3D modelling and assembly. There is still controversy about whether VR is more suitable for modeling tasks than traditional CAD mode. Research supporting VR believed that participants have a better modelling experience in the immersive environment than in desktop systems because of the unrestricted interaction mode (Johansson & Ynnerman, 2004; Forsberg *et al*., 2008). LaViola *et al*. (2017) emphasised that the interaction way of traditional CAD mode (with the mouse and screen) is not intuitive for the 3D operation tasks (Fechter *et al*., 2022). However, Wang *et al*. (2004) did not think an immersive VR system could completely replace desktop workflow, but the author accepted the performance of a desktop VR system (Toma *et al*., 2012). Recently, Zignego & Gemelli (2020) also presented a similar view. The author confirmed the practicability of VR to 3D model simulation but questioned the applicability of product aesthetic evaluation (Berni & Borgianni, 2020).

According to the above review, this section found the following key insights from VR and CAD in Design:

(1) VR-CAD is developed in order to handle better and operate the virtual prototyping;

(2) VR-CAD applications focus on human-computer interaction, especially in modelling and assembly of the 3D models;

(3) the 2D viewing mode of traditional desktop devices (projected 3D models on a 2D screen) limits the depth perception of rendering effects on 3D models;

(4) currently, there is no consensus on whether VR is more suitable for design evaluation than the traditional CAD approach.

## Section 2.5 VR Environment

### Section 2.5.1 VR Display and Context Generation

VR provides users with an immersive experience through stereo vision and head tracking. The visual cone generated by the users' eyes makes the virtual object mistaken for a part of the real world. The head tracking technology allows users to move freely from their perspective in the virtual environment, thus enhancing the experience of the virtual space. VR's display device includes a variety of configurations (Berg & Vance, 2017), such as large screen projection (Powerwall), multiple connected projection screens (CAVE), and the Head-Mounted Display device (HMD). The typical feature of a semi-immersive VR system is to display stereoscopic images by projector or display (Weyrich & Drews, 1999; Mujber *et al*., 2004; Morar & Macredie, 2004; Wang & Li, 2004; Huang *et al*., 2004; Hoffmann *et al*., 2006; Choi & Cheung, 2008), while CAVE and HMD could provide fully immersive VR visual experience (Bowman *et al*., 2001; Mendes *et al*., 2019). The desktop VR system is portable and easy for the designer to operate, but with the limitation of insufficient immersive effect. CAVE system provides powerful visualisation for collaborative applications, but its large-scale development in the market is hindered by the high cost and complex installation process (Li *et al*., 2001; Creagh, 2003; Fairén *et al*., 2004; Narayan *et al*., 2005).

As the mainstream display device developed by VR technology, HMD provides the critical cue of the brain's stereo vision and depth perception, that is, the 3D content in binocular parallax. The first HMD device (SuthLand, 1968) consists of two head-mounted cathode ray tubes. Due to its heavyweight, the equipment can only be fixed to the ceiling. At that time, SuthLand (1968) proposed that if VR technology is expected to provide images that eyes can receive, the images must be the same as those received by people in the real world. This idea is still the primary goal of VR development. Stakeholders are trying to solve the problems of HMD's bulky body, display resolution, and effectiveness. Since 2010, listing several representative HMD devices such as Oculus, Samsung, Google, and HTC indicates that the application potential of HMD has been developed. Up to now, the HMD system is still not optimizing enough, but the development of HMD vision technology has supported the equipment needs of various disciplines. In addition to the products sold on the market, researchers are also constantly trying to improve the HMD experience. For example, Banks *et al*. (2016) and Lambooij *et al*. (2009) proposed the development of HMD devices with adjustable eye focus to realize natural depth perception (Yu *et al*., 2019). Davis *et al*. (2015) showed that VR sickness could be alleviated using low delay inertial devices and intelligent rendering schemes (Mendes *et al*., 2019). Yu *et al*. (2019) summarised the significance of multi-layer displays to HMD development.

In addition, the game engine often determines the generation of VR content. Currently, standard game engines in the market include Unreal Engine 4, Unity, and CryEngine. The use of programming script language provides potential researchers with the possibility of VR research (Kleiner *et al*., 2007; Scarfe & Glennerster, 2015). This is because the game engine can provide research-oriented calculation results and allow the simulation of a highly realistic visual environment, just like conventional modelling software.

### Section 2.5.2 VR Studies in Embodied Cognition

Embodied cognition studies how we think and understand the interaction with the environment (Varela *et al*., 2017). The research fields of embodied cognition include artificial intelligence to cognitive neuroscience and have also been widely discussed in interaction design (Hummels *et al*., 2008; Loke & Robertson, 2013; Svanæs, 2013; Van *et al*., 2104). Groth (2017) believes that embodied cognitive theory helps to provide information for the design and process-related practice. Kirsh (2013) explored how embodied cognition theory can be used as the human-computer interaction design and development principle. Shin & Biocca (2018) explained how the immersion felt by users in VR affects the immersive storytelling and experience. The author believes that the user experience in VR depends on personal characteristics. McMahan *et al*. (2016) also discussed these issues. The results of these studies emphasise that the satisfaction of immersive experience is responded by users' perception and intention (Reinhard & Dervin, 2012; Trentini, 2015; Hamari *et al*., 2016). Nowadays, the research of embodied theory in VR mainly focuses on evaluating the visual or interactive experience and virtual avatar (Goldin-Meadow *et al*., 2001; Yuan & Steed, 2010; Jo *et al*., 2017; Pan & Steed, 2019). Because of the embodied experience created by immersive VR, users can experience sensory cues in the virtual environment. Therefore, immersion is regarded as a part of the cognitive dimension. The consciousness, sense of presence, empathy, and contextual experience help users integrate into the virtual environment. Bozgeyikli *et al*. (2021) compared the effects of VR visual fidelity and view scaling on user experience and task execution. The results show that low visual fidelity can improve task execution, high fidelity can enhance presence and dizziness, and view scaling does not affect the user experience. Due to the visual perception of materials often affects the presentation of design effects. Structuring a customer preference model with predicted performance is beneficial for understanding users' cognition of product materials. In the design evaluation stage, users' embodied cognition of materials may be the direction of design guidance, but this theory has not been widely discussed. A broader overview of VR can optimize the technology to support more design functions.

In these studies, scholars paid attention to the usability of VR applications in specific design directions but still lacked a comprehensive understanding of how users perceive materials in VR. Because of the applicability of VR technology, the VR research should supplement the overview of this technology, especially in material perception, to establish design guidance that is easy to understand in the product design stage.

According to the above review, this section learned the following key insights from VR Display and Context Generation:

(1) at present, VR devices that provide immersive experience are mainly realized through HMD;

(2) the generation of VR visual content depends on the game engine;

(3) an immersive experience in a VR environment is regarded as a part of the cognitive dimension.

## Section 2.6 Research Gaps

In industrial and product design research, designers and scholars have paid much attention to the theoretical framework of the relationship between material perception and user experience in the past decades. Although, the development of material perception and its influence on material visualisation are also discussed. As outlined, these research results can be reflected in the relevant theoretical basis of material visualisation and visual perception in future product development.

Based on the previous sections, as far as the current research on material perception in the field of design evaluation is concerned, the interpretation of the relationship between material visualisation and virtual reality is insufficient. However, it is necessary to explore this field, especially for the application and research of using VR devices as a design medium to replace the 2D visual input device.

According to the research overview, the existing research gaps in this study are listed as the following three points:

*Lack of research in material identification in VR environment.*

Although some studies have covered the investigation of VR in design and material perception, the application scenarios of these studies are mainly on packaging design (Ohkura *et al.*, 2019; Di Cicco *et al.*, 2021), automobile design (Shao *et al.*, 2012), and interior design (Schnack *et al.*, 2019). From the application's perspective, these studies pay more attention to the impact of material colour and aesthetic effect on user perception in the VR environment. The methods of this kind of research are mostly similar. Take Fiorentino *et al.* (2002) as an example, although the technology is based on 3D visualisation with adjustable material parameters to improve user perception. However, the user experience is mainly considered from the interaction level rather than sensory recognition. Moreover, even though many studies have confirmed that binocular parallax is beneficial in judging material properties, most focus on exploring combining VR and tactile feedback. This research is very instructive and practical for the actual material experience. However, the study in this thesis focuses on the visual level. There is no rich and clear research as guides for how people recognize materials in VR.

*Unclear about the different impact of viewing modes on users' feeling.*

Many studies have compared user experience in immersive VR environments and traditional desktop environments, this comparison involves the modelling and assembly research of 3D objects. Such studies have fully shown that the VR does not only present single sensory information but also a way closely interweaving perception and action with the visual environment (Ellis, 1995; Thelen & Smith, 1996; Clark, 1998, 2008, 2013; Tarr & Warren, 2002; Shapiro, 2010; Scarfe & Glennerster, 2015; Varela *et al*., 2017). However, perceptual differences are reflected in physical and visual interactions and provide perceived cues. The interactive content and visual habits created for traditional 2D viewing mode cannot be directly transferred to VR application scenarios (Toma *et al*., 2012). Generally, it is necessary to re-evaluate the visual perception in VR to obtain an improved presentation impression for users. The comparison between VR and traditional 2D viewing modes should be transferred from the perspective of human-computer interaction to visual perception. Otherwise, researchers may focus on the differences in users' behaviour rather than the visual perception.

*Limited research on how synthesized materials represents in a VR environment.*

The rendering effect of materials determines their visual similarity with natural materials. This work is related to the BRDF algorithm of the rendering engine and the adjustment of material parameters. However, the simulation parameters of material for the VR environment have not been established. Another research deficiency is that since the engine was developed for 2D display mode, the adjustment and review of material parameters are observed based on a non-immersive desktop environment. However, whether the results of this visual review are consistent in VR has not been further explored.

Using design tools promotes the smooth progress of the design evaluation process and obtains ideal evaluation feedback. Therefore, it is necessary to clarify the scope of standardized use in the design process. In addition, the material perception provides the possibility of conducting empirical research in a meaningful way for the subsequent development of VR software to develop and optimize the application details.

# Chapter 3 The Perceptual Differences between VR and 2D Display Mode

## Section 3.1 Introduction

Industrial design mainly solves the problems of product shape, colour, and material, and the ultimate goal is to meet consumers' needs, which is mentioned in Chapter 1. The process in product design has already changed from product-centred to user-centred. Therefore, designers begin to attach importance to the users' experience and feelings about product design. The background of design evaluation emphasises when people evaluate the design content, the evaluator can perceive the surface material of the product design sketch through the eyes (Papagiannidis *et al*., 2014). Because of the manufacturing process and other reasons, there are significant differences between the surface material and the material displayed in the effect drawing of the physical product (Tang *et al*., 2017). Based on this, in the exploration of this chapter, the study focuses on the experience of users' visual perception of materials.

In our daily lives, people will face or contact various materials, such as plastic, metal, wood, marble, water, jam, cotton, etc. These materials have different physical and optical properties, which determine how we interact with them (or avoid them) (Fleming, 2017). Material perception helps people decide which interactive method is more appropriate before contacting the objects. Material perception is a feeling and impression of material based on the visual perception of material surface characteristics, such as texture and smoothness. At the same time, material perception is also produced by the brain's comprehensive processing of the surface characteristics of materials perceived through vision. In fact, as the thesis mentioned earlier, realistic image synthesis depends not only on illumination but also on accurate simulation of the virtual scene, and the challenging task is to assign appropriate material descriptions to each object in the scene (Vangorp *et al*., 2007).

Therefore, people's visual system is susceptible to the materials' appearance, and the imperfect approximation cannot meet the users' requirements (Adelson, 2001). Virtual reality technology is a new cognitive tool that emphasises perception ability based on human feeling. Immersion is considered an essential performance measure of virtual systems, and the reason for immersion is that users have a sense of existence or hallucination similar to natural objects in the virtual environment. Virtual objects are similar to natural objects but even more realistic than real objects to achieve an immersive effect (Calvo *et al*., 2017). This is different from traditional design presentation modes, such as displayed the 3D models on the 2D screen. Although both modes are entirely applied to design evaluation. VR can create more ecologically stimulus programs and reflection schemes than traditional display devices to help experimenters better control the environment (Wilson & Alessandro, 2015). At the same time, the immersion and visual fidelity provided by VR can stimulate some psychological reactions of the testers. Therefore, in order to understand and describe the material perception in the VR environment, it is necessary to clarify the differences between the VR visual environment and the traditional 2D viewing mode. This is also the significance of this chapter as a pilot study.

### *Structure of the Chapter*

Material representation has always been an important part of visual effects in industrial design. And the judgment and recognition of product material often remain on the rendering effect drawings of the 2D display. However, it cannot fully intuitive performed, even sometimes cannot identify the specific material composition. As a device to simulate the natural environment, VR strengthens people's immersive experience by its 3D sense of space. In this chapter, this research answer whether the material perception in VR is different from that in traditional 2D mode. This chapter presents a comparative experimental study conducted to analyse the visual effect of VR compared to the feeling of traditional 2D viewing mode for the material perception on geometrical 3D models. It is hypothesized that the two display modes would bring different viewing experiences to the users, henceforth resulting in different perceptions of the same materials. In this chapter, the research based on the following question:

> *"In the VR environment, whether users' perception of materials is different from the traditional 2D viewing modes?"*

The Related Works section introduces the previous research on 2D and VR visual perception. In the User Study section, the overall framework and process of the research are shown. The materials and simulation methods selected in the comparative experiment are further described, which depend on the rendering software. In the Results part, the analysis is divided into two steps, there are: for the test results of two objects presenting materials, and the performance of the two devices is analysed. In the Summary section, this chapter roughly reflects on these impacts based on the significance of VR and traditional patterns to design evaluation introduced earlier.

## Section 3.2 User Study

This chapter aims to test whether users feel differently when they use different devices (computer and VR) to observe the object with the same materials. Therefore, the experimental process mainly uses software to simulate different materials, recording the users' feelings after using the devices to observe the materials separately.

### Section 3.2.1 Apparatus and Display

The laboratory compares the material images presented by the two viewing devices, so the equipment information applied is as follows:

- Devices Details: In terms of VR viewing mode, this study used the headset, HTC Vive Pro. As for the traditional 2D viewing mode, the image stimuli were presented one at a time on a calibrated 4.5Ghz gaming laptop Alienware AREA-51 M with 17-inch.

- Visual Distance and Size: The viewing distance was set to 500 mm, and the image and display size was 1920 pixels by 1080 pixels in the two-viewing mode.

- Field of View: In order to avoid the test error caused by the freer perspective of VR, this study chose a fixed head display. Participants can only watch the front view of the test object.

- Display Software: AutoDesk 3DS Max is used as the software for 2D display that builds basic geometric models according to requirements and then uses light and camera to adjust the visual effects of each perspective. For rendering images, this study used the VRay plug-in to make the materials of the 3D model objects more natural. Because VRay allows us to adjust the lighting and materials properties on the models (Hendratman, 2012). For the test image of the VR device, this study uses HTC VIVE as the VR display. This study is relying on Unreal Engine4 (UE4) to create geometry and rendering tasks. UE4 contains rendering code and design tools that can be used to build 3D models. The Unreal Engine's source code can help designers simulate whole new scenes, whether indoors or outdoors, and visualize 3D scenes from the perspective or stereo view of Unreal Engine (Qiu & Yuille, 2016).

### Section 3.2.2 Material Stimuli

As far as the choice of experimental target is concerned, the material which is greatly changed by environment or illumination should be avoided as much as possible. Identification of a material belonging to a particular category can be based on the properties and parameters of the material in the relevant information (Fleming *et al.*, 2013). Berzhanskaya *et al.* (2005) have experimentally proved that the spatial distribution of surface gloss perception is inconsistent, and it is affected by specular reflections. For translucent materials like ceramics, information such as specular highlights, rendering, and background environment dramatically influences the estimation of glossiness. Although BRDF tries to separate reflectivity and material-related information, this technique does not consider the texture and geometric shape influence factors. The same reflectivity properties can be observed on the surfaces of different materials (Sharan *et al.*, 2013). In addition, transparent materials cannot be generalized by a single reflection function (Szeliski, 2010; Herbort & Wöhler 2011). Due to the complex optical properties of translucent or transparent materials, this study includes only opaque materials in this study, and the tested object in the experimental stage is a kettle that consists of stainless steel and plastic materials. Therefore, in order to ensure the objectivity and scientific rigor of the follow-up rendering task, this study carried out the following rendering and testing process according to a picture of a kettle (as the Figure 3.1 shown) so as to avoid the increase in rendering difficulty and visual viewing error caused by the influence of illumination and environment on the natural objects.


*Figure 3.1. The physical picture of the kettle as the test object.*

This study focuses on the difference in material perception under different devices, so the rendering process is mainly to create the 3D geometry to represent the object and give the related material for the subsequent contrast stage. In the field of industrial design, spheres are often used as the basic models to visualise material parameters. The sphere possibly presents all surface directions to the observers. Its convexity eliminates the need for its own shadow and mutual reflection. Nevertheless, Vangorp *et al*. (2007) indicated that the geometric shape of the object would affect the material perception and that the sphere was not necessarily the most straightforward shape to distinguish, which depends mainly on the type of material or the shape similar to the target. However, in this study, the reference group was selected is a photo of a kettle whose shape is similar to the deformation of a cylinder. Therefore, in order to avoid the influence of object shape on material perception, this study choose to create two geometries, cubes, and spheres, to be the models to test the effect of plane and surface on material perception.

As for the traditional 2D viewing mode, according to the picture of a kettle in the previous statement. This study used the picture to adjust the parameters of material attributes in VRay to simulate the material appearances. Afterward, the adjusted materials were assigned to the cube and sphere, and four pictures were rendered for participants as a test image of the computer (as shown in Figure 3.2). Like AutoDesk 3DS Max, this study used UE4 to build 3D models of cubes and spheres in VR viewing mode and used its renderer to adjust stainless steel and plastic materials depending on the picture of the kettle. In order to minimize the error of material presentation in the contrast process, the material attributes and lighting positions in UE4 are the same as the details of the VRay adjustment, and then four projects are generated (shown in Figure 3.3).

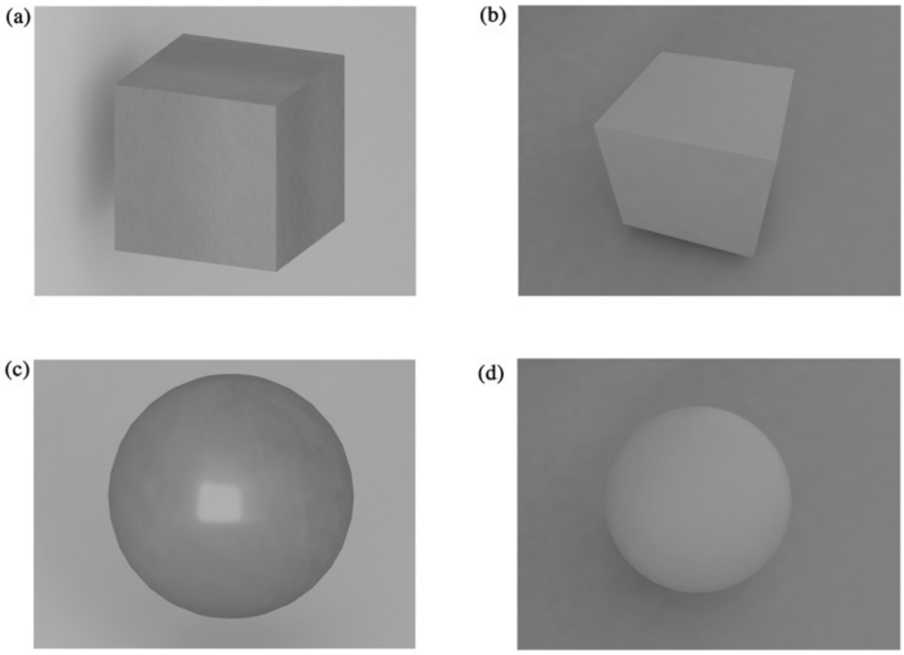

*Figure 3.2. The test image of 2D display: (a) cube made of stainless steel, (b) cube made of plastic, (c) sphere made of stainless steel, (d) sphere made of plastic.*

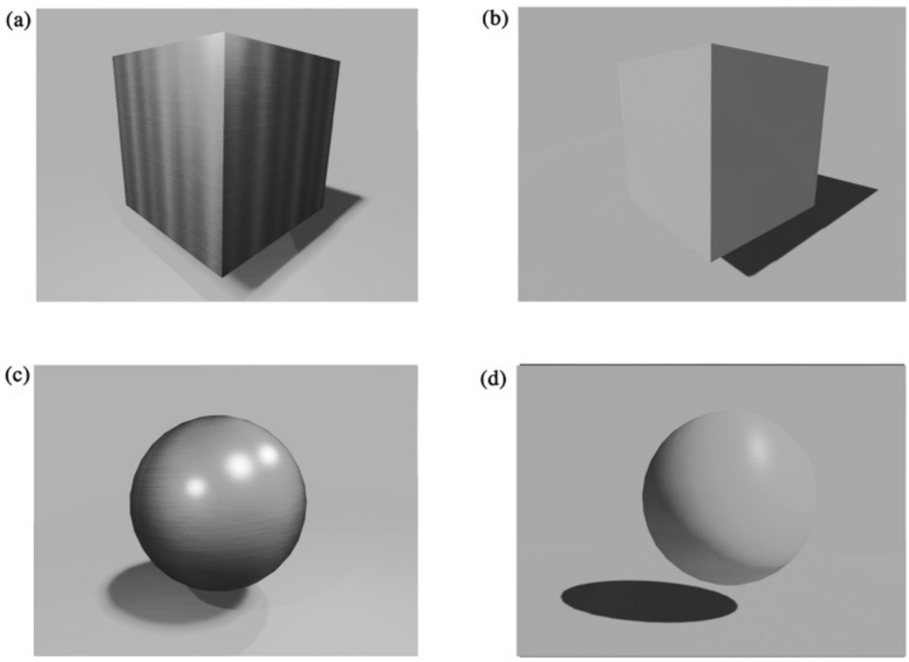

*Figure 3.3. The test image of Virtual Reality: (a) cube made of stainless steel, (b) cube made of plastic, (c) sphere made of stainless steel, (d) sphere made of plastic.*

### Section 3.2.3 Participants

The selection of participants, expected to respond quickly to perceived materials, primarily considers their knowledge of product design and the relevant field. The research context is also highly connected with product design and material evaluation. Having the participants with a design background would assure a basic understanding of material features and functions on a product. Besides, the participants would usually have experience at working with CAD software, therefore the familiarity with the digital representations of product models. Therefore, this study does not consider the user's design experience as an influencing factor. This study recruited 30 participants aged 19–34 (18 males and 12 females) for the test ($n = 30$, $M = 22.8$, $SD = 1.32$), which took place at the Xi'an Jiaotong-Liverpool University. They were students and researchers from industrial design and architecture education backgrounds, and only 9 of them had VR experience. The whole study plan was approved through the University Ethics Committee established in the Xi'an Jiaotong-Liverpool University.

### Section 3.2.4 Procedure

This test was divided into two parts: one was to test the effect of material performance displayed on the cube object under VR and 2D viewing modes, and the other was about the sphere's test for material perception. The experimenter introduced the experiment process to the participants and showed them the kettle picture (Figure 3.1) as the comparison reference. Asked them to observe and remember the visual effects of the material on the picture.

In the test of the cube model, the stainless steel and plastic were selected as the stimulus. The devices illustrated the material visualisations of related materials attached on the cube model. Under the 2D viewing mode, the rendered material effect was shown in the computer its entirety, participant can compare the visual effect with the reference picture. Under the VR viewing mode, participants using the fixed-HMD to observe the rendered material and compared with the reference picture after they took off the HMD. Both visual effects were identical in every other way. This test first asked participants to compare the stainless-steel material under VR and 2D viewing modes, and they were asked to record how close they thought the material were to the actual stainless-steel material (on the kettle's picture). As measured on the 10-point scale, where 1 represented little similar, and 10 represented much similar. After that, the participants also had to compare the perception of plastic cubes in VR and 2D viewing modes and still assess the similarity between the material content presented by the two devices and the kettle picture. The test still requested participants to evaluate the similarity of plastic materials based on the 10-point scale. The testing process is shown in the following Figure 3.4. The scoring mode is in the form of oral interview, the researcher asked the participants with the similarity of observing materials on different devices, and recorded the scores. The steps of the two experiments are the same, only the differences from the test models.


*Figure 3.4. The testing process of the participant: (a) observe the material on the 2d display image, (b) observe the material on the VR device.*

## Section 3.3 Results

On the one hand, as a rising visual medium, VR technology meets the needs of guiding users by the vision and enhancing the realistic experience through the interaction of other senses (Han & Kim, 2017; Idris & Ahmed, 2020). On the other hand, the traditional desktop view mode projects the visual images onto a 2D screen, which has obvious limitations for visually displaying the visual effect of 3D models. The stereo vision provided by VR technology is regarded as a solution. However, the current research in this field does not explain the difference between VR and traditional 2D viewing modes based on material perception. It cannot provide more effective and convincing suggestions for applying visualisation tools in subsequent design activities. The main challenge of product design is to create a valuable product experience and deliver it to users effectively. Based on this, the starting point of this thesis is to explain the material perception in the VR viewing mode. Specifically, this raises the question of how users perceive the material visualisation when VR is applied to design evaluation for designers who are used to evaluating with the traditional 2D viewing mode.

As this study has pointed out, the main objective of this study is to explore whether users have different experiences in material perception by VR and 2D display. Therefore, it is necessary to determine the extent to which the images presented by the two devices are close to the actual material. Also, the research still confirms that the analysis of the test objects focuses on this. Factorial Analysis of Variance (F-ANOVA) is used to analyse the test data of two kinds of equipment and materials. The factorial ANOVA determines whether the individual and interaction of each factor have a statistically significant impact on changing user perception of material (Collins *et al*., 2014). The experimental data do not take into account the gender impact.

### Section 3.3.1 Cube

A one-way between-subjects ANOVA was run with materials (stainless steel and plastic) and displayed devices (VR and 2D viewing mode) as the independent variable, and perpetual result as the dependent variable. Table 3.1 shows the analysed results of the cube test. If $p < .05$, significantly changes in the corresponding factor affect the participants' perception of the material. Results of the ANOVA showed a significant difference between the devices [$F(1, 116) = 13.096$, $p < .001$] on perceptual results, which means that the viewing modes had a significant impact on the participants' material perception. There is no statistical significance for the significance analysis of materials [F (1, 116) = 1.378, p = .234].

*Table 3.1. ANOVA results and descriptive statistics for the cube.*

| Variable | Mean | SD | n |
|---|---|---|---|
| Stainless steel | | | |
| VR | 6.57 | 1.006 | 30 |
| 2D | 5.97 | .928 | 30 |
| Plastic | | | |
| VR | 6.38 | .935 | 30 |
| 2D | 5.75 | .859 | 30 |
| Source | df | F | *P* value |
| Materials | 1 | 1.378 | .243* |
| Devices | 1 | 13.096 | <.001* |
| Error | 116 | | |

*Significant difference at α 52= .05

Figure 3.5 displays the mean plots of the material perception on the cube model. The blue line represents VR display, and the red line represents 2D display. For stainless steel materials, the analysis revealed that the VR viewing mode (n = 30, M = 6.57, SD = 1.006) has significantly higher score on average than the traditional 2D viewing mode (n = 30, M = 5.97, SD = .928). In the score of plastic materials, the scores of the VR (n = 30, M = 6.38, SD = .935) is still higher than that in the traditional 2D viewing modes (n = 30, M = 5.75, SD = .859). It can be emphasised that participants feel the content presented by VR is closer to the actual material on the picture than that presented by the traditional 2D viewing modes.

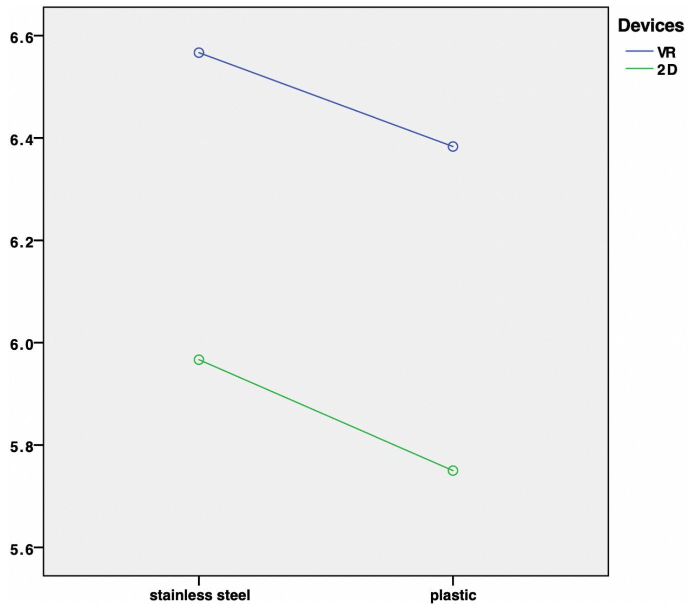


*Figure 3.5. Mean Plots of Cube Testing.*

## Section 3.3.2 Sphere

Table 3.2 shows that the variations of the device [F (1, 116) = 10.605, p = .001] significantly affect participants' feelings about the material for the sphere model. The same as the previous analysis result, the analysed result of the material [F (1, 116) = 0.255, p = .615] is not statistically significant. Therefore, the factors that affect the user's rating are caused by the viewing mode.

*Table 3.2. ANOVA results and descriptive statistics for the sphere.*

| Variable | Mean | SD | n |
|---|---|---|---|
| Stainless steel | | | |
| VR | 6.83 | 1.003 | 30 |
| 2D | 6.35 | .975 | 30 |
| Plastic | | | |
| VR | 7.03 | 1.159 | 30 |
| 2D | 6.33 | .813 | 30 |
| Source | df | F | *P* value |
| Material | 1 | 0.252 | .615* |
| Devices | 1 | 10.605 | .001* |
| Error | 116 | | |

*Significant difference at α = .05

The mean plots of the effect of material perception on the sphere model are shown in Figure 3.6. For stainless steel materials, it can be seen that the participants prefer VR (n = 30, M = 6.83, SD = 1.003) more than computers (n = 30, M = 6.35, SD = .975) according to content similarity. As for plastic, the scores of VR (n = 30, M = 7.03, SD = 1.159) still higher than that in the 2D viewing mode (n = 30, M = 6.33, SD = .813). The first alternative hypothesis that there are material perception differences between VR and traditional 2D viewing modes would be accepted. Furthermore, according to the mean plots of the data, this study found that the material performance of the sphere is more helpful for observing the materials rather than the cube in the process of user identification.

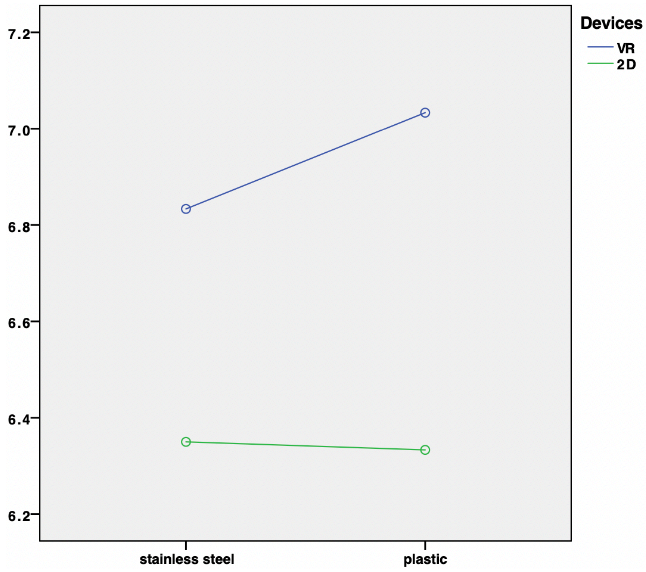


*Figure 3.6. Mean Plots of Sphere Testing.*

In addition, according to interviews with the participants, this study found that most participants believe the texture effect of materials appearance in the VR environment is more evident and authentic than that of 2D images. At the same time, because of the stereoscopic and immersive effects, the overall visual perception of VR is also better than the traditional 2D viewing mode. Nevertheless, some participants stated that even though the visual effect of VR was similar to the actual materials, it was not as smooth as the 2D image.

## Section 3.4 Discussion

Immersive environments allow the participants to effortlessly remember more of their surroundings (Sutcliffe et al., 2005). One of the main features in the VR system is the introduction of stereo depth, which gives users the illusion that they can see physical objects in virtual space (Wann et al., 1995). The rendered materials with authentic and high-quality effect is the core element of the reality and immersion provided by the virtual environments. Vangorp et al. (2007) and Bonneel et al. (2010) also have investigated the changes in users' perception of vision and auditory under different conditions of rendering quality in virtual environments. Wilson & Alessandro (2015) have discussed how humans recognise and perceptive the space in an immersive virtual environment provided by VR. It is found that VR can present visual stimuli along 3D planes, which is more conducive to stimulating participants' behaviour than traditional experimental schemes (Adelson, 2001). Ankomah & Vangorp (2018) reviewed the research on VR telepresence in previous years. The author stated that users could deepen their sense of presence in the VR environment by vision, even if there is no behavioural interaction. Virtual reality provides near-real visual effects, which may be a good tool for material perception and the experience of designing effect maps. As a medium of visualisation and communication, VR demonstrates all dimensions of VP and helps individuals better understand the model.

Every object is made of materials, and we usually know what it is by observation. Nature provides us with a neural architecture that recognises the essential elements of certain materials in images even without training (Cichy et al., 2016). Early visual perception work focused on the human visual system's physiological and neurological characteristics, such as contrast and colour. For example, in the study of colour constancy, Brainard et al. (2010) found that the colour and brightness of objects remained distinctly unchanged under substantial changes in light. Obein et al. (2004) proved a similar invariance of perceived glossiness under varying illumination, that is, glossiness invariance. Xiao & Brainard (2006) showed that the appearance of material is indeed slightly affected by gloss. It can be proved from the perceptual perspective that people perceive materials by observing objects made of them rather than consciously considering the psychological model of abstract reflectance function. Previous studies have been carried out in many pieces of literature. Scholars believe that human vision depends on images related to material properties (Nishida & Shinya, 1999; Fleming et al., 2003; Fleming et al., 2005; Motoyoshi et al., 2007; Ho et al., 2008). The meaning of materials cannot be realised by simply defining and designing a product's appearance. When users are asked to describe materials, they often take the observed material information as examples to illustrate what they perceive. In this study, the material representation is realised by simulating the material visualisation of actual products. As a reference, the materials' photo timely helps participants to give appropriate ratings. Plastic and stainless steel (a type of metal) were selected as the materials displayed in this study because they were widely used in previous experimental work (Giboreau et al., 2001; Tiest & Kappers, 2007; Veelaert et al., 2020). In our case, this study requires participants to evaluate the similarity between materials and photos and take the evaluated score as the basis for analysis. Therefore, material characteristics such as colour and texture are not considered in this comparison. On this basis, the research results show that the difference in users' perception of the same material under two viewing modes has a significant impact.

## Section 3.5 Summary

This chapter describes the difference between the visual experience of materials in VR and the traditional 2D viewing modes, answer the material perception in VR in the low-level stage of visual system. In the beginning, this study introduced that visual material perception is one of the primary methods for people to understand objects, including their physical and optical properties. Influenced by illumination and shape, people also face some challenges in identifying materials, especially in today's common design activities of 3D models. This process also emphasises that the evaluation mode that observed on a traditional 2D screen is not intuitive. Many studies have confirmed that VR can enhance user experience and interaction in virtual environments. As a tool for the immersive experience, VR has been widely used in the field of design, making use of its immersive visual effect to create a realistic environment. This chapter explore whether VR can be used as a tool for designers and users to perceive material by its immersion and stereo sense. AutoDesk 3DS Max and Unreal Engine are used to manipulate and render the contents for computer and VR displays, respectively, based on the material for testing object pictures. In order to ensure the rendering effect, the material parameters are treated the same. Participants were invited to observe the material with two devices, compared with the previous picture, and scored according to the similarity. The study found that the perception of plastics and stainless steel on the cube or sphere test was more obvious and intuitive in VR than that in the 2D display. Some participants said that the material texture observed in VR was more apparent, which helped them to identify material types more quickly. The study in this chapter stated that VR provides the users with stereoscopic effects not seen on the 2D display. This feature seems to deepen the perception of material, which may facilitate the design of industrial products, furniture design, automotive interior and so on.

Based on this finding, the next step for the mid-level vision of material perception, the research focuses on measuring and quantifying the differences between participants' perception and recognition of material properties in VR and traditional 2D viewing modes.

# Chapter 4 Difference of Users' Judgement in Material Properties under VR and 2D Viewing Modes

## Section 4.1 Introduction

In the previous chapter, users have different perceptual experience when they use VR and computer to observe material simulation. Such a result is related to the imaging mode of the device. Based on the experimental results, the research measure and verify further the performance of this visual perception difference. In order to generate a convincing representation of the product, the designers often need to choose, simulate, and synthesise the surface materials attached to the virtual model. This can be a challenging task (Ferwerda et al., 2001). The final material appearance depends heavily on the editing and rendering of materials, and Hiramatsu et al. (2011) indicated that perceptually sound materials require a comprehensive analysis of surface colour, texture, and light reflection. The synthesized surface material properties can be represented computationally as a reflectance model (e.g., BRDF) in the rendering process. Visual properties in rendering engine such as the glossiness or roughness of materials can be simulated by varying the relevant parameters in such computational models. The perception of the visual properties depends on how the virtual object is rendered and displayed to the viewers (Schifferstein & Cleiren, 2005; Tiest & Kappers, 2007). Fleming (2014) pointed out that people have the ability of material recognition and perception to form a vivid impression of material characteristics, no matter whether they are familiar with the materials they see or not. The realistic rendering of surface materials is the core element of the overall evaluation of the intended design representations (Vangorp *et al*., 2007). Another important visualisation task is to present multiple visual perspectives of a model. In conventional CAD programs, designers or users usually use the mouse to rotate the model on the two-dimensional projection plane to browse all facets of a three-dimensional product model. (Piegl, 2005; Satter & Butler, 2015). Vangorp *et al*. (2007) claimed that in the traditional 2D viewing mode, people evaluated and perceived model materials according to the conditions of lighting and rendering, which would also affect the ability of people to select and evaluate materials when observing the model. Therefore, material appearance, as a visual expression, is the user's first impression of surface materials, and material characteristics, as a material feature, constitute the user's visual clues for judging materials. The user's perception of material properties is affected to some extent by the viewing mode. Judging the user's perception of material properties reflects the impact of viewing mode on the user's perception results. Based on the research results of Chapter 3, this chapter focus on the users' judgement of material properties. It is worth noting that the material properties mentioned here are based on the properties of the material visualisation effects in the rendering engine, which are explained in section 4.2.1.

Traditional 2D viewing devices rely on CAD software to perform tasks. CAD techniques generate digital models of products and are committed to simulating the physical appearances of product prototypes (Martin et al., 2017). Product prototypes serve as an essential medium to obtain early user feedbacks and optimize the user experience. Design evaluation is thus supported with a higher fidelity of simulation (Choi & Chan, 2004; Bordegoni et al., 2006a). Several recent studies have shown that virtual prototypes can be a cost-effective solution for evaluating design concepts (Choi & Cheung, 2008; Kim et al., 2002; Antonya & Talaba, 2007; Hu et al., 2011; Abidi et al., 2013). In that sense, the perceived quality of the rendered prototypes may influence the evaluation results, particularly the visual aspects. In the other hand, VR devices integrate stereoscopic 3D rendering to provide a more immersive viewing experience (Drouhard et al., 2015). Some studies showed that VR interfaces produced better depth perception and viewing experience, henceforth improving the designer's intuitive understanding of a CAD model (Johansson & Ynnerman, 2004; Toma et al., 2012; Satter & Butler, 2015; Berg & Vance, 2017). However, the scientific understanding of material perception and its applications in VR is still fairly limited. Several studies in vision research have shown that the visual judgment of the surface characteristics of materials is not independent of the observing conditions (Sève, 1993; Fleming et al., 2003; Geisler, 2008). Van Dam et al. (2002) argued that VR has the potential to display a larger quantity of meaningful data and facilitate more natural interaction than traditional 2D visualisation displays. VR also provides a better user performance in comparison with the traditional 2D viewing mode (Rhiu et al., 2020). The unique depth and immersive effect produced by VR may influence how we perceive rendered materials in such viewing environments.

### *Research Approach*

Visual perception explores the essence of visual cognition, stimulates new discoveries, and reveals the limits of visual communication (Rensink, 2021). On the one hand, these are important factors for human visual systems to recognize particular materials. They function as monocular cues that can be presented on a traditional 2D viewing mode. On the other hand, it remains ambiguous whether the stereoscopic disparities between the two projected views of material features would influence the impressions of rendered materials (Gibson, 1978). Moskowitz (2020) argued that psychophysics had a direct impact on product design, which should be regarded as an expected impact. In this chapter, psychophysics is selected as the research approach. Designers can use psychophysics as a tool to understand how components (stimuli) drive responses (user perception). Based on industrial or product design background, the purpose of design evaluation is to ensure the subsequent product development. Therefore, researchers and designers try to establish the relationship between material perception and physical parameters to quantify the data for subsequent practical applications.

### *Structure of the Chapter*

In this chapter, this research answers the following question:

> *"Where does the difference lie between users' judgment of material properties, based on VR and 2D viewing modes?"*

In the real-time rendering context, this chapter explores the perception of surface materials in traditional 2D viewing mode and immersive viewing environments. The two viewing modes when viewing the same scene are shown in Figure 4.1. Using psychophysics methods, this study starts with establishing the perceptual scale of the changes in material appearance. The obtained perceptual scale is then used as the measurement to compare the viewer's performances on material properties judgments in 2D and VR viewing modes. It is hypothesized that the performance would be different when a surface material is viewed stereoscopically in an immersive viewing environment, in which the strong sense of 3D depth (Matsushima *et al*., 2012) could influence the perceived material appearances.

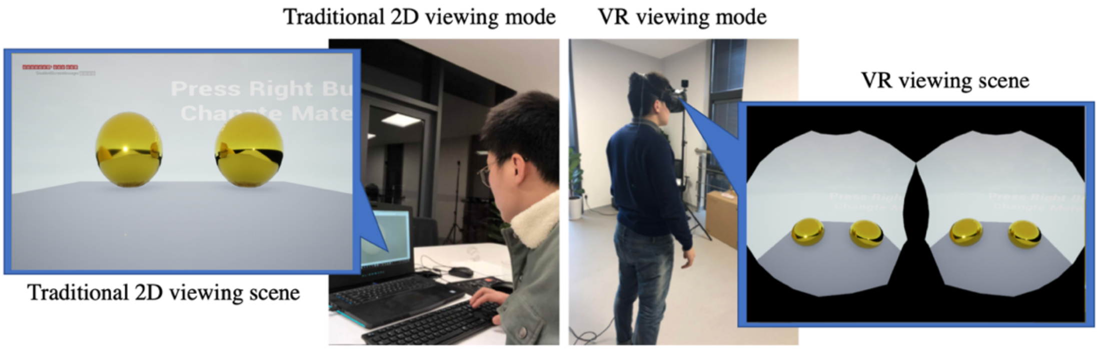


*Figure 4.1. Traditional 2D viewing mode (left) and immersive (VR) viewing mode (right).*

## Section 4.2 User Study

Psychophysics emphasises the relationship between quantifiable physical stimuli and users' consciousness content (Liang & Acuna, 2020). When the change of physical stimulus intensity can be perceived by the human visual system, it will be evidenced by the Just Noticeable Differences (JND) (Wolfe *et al*., 2006). Based on the psychophysics approach, this study uses the Method of Adjustment (MoA) to measure the users' JND of material attribute changes. The method of adjustment requires that the examiner specify a perceptual criterion to the subject, who adjusts the stimulus to satisfy the criterion (Pelli & Farell, 1995; MacLin *et al*., 2008). However, adjustments are essentially the subjective reflection of the subjects because the data obtained depends on the subject's understanding of the perception standard. This method can generally provide ideal data quickly, with more general applicability, and is often used to measure physical stimulus parameters. The JNDs are analysed with fitted response curves and inspected with its conformity to the Weber's law. Weber's law describes the relationship between the perceived changes and the actual changes in stimuli (Quadri & Rosen, 2021). Each point on the fitted curve reflects a distinguishable stimulus intensity and can accurately reflect the mapping back to causal conditions (RichardWebster *et al*., 2018). The research obtains this perceptual scale and use it as the measurement basis for the perceived material attribute changes. This allows us to carry out a series of material matching tasks to investigate the difference in the users' judgments on material attributes between 2D and VR viewing conditions.

The experiments were conducted in the Xi'an Jiaotong-Liverpool University. All of the participants were recruited from the students studying in the university. In order to avoid test errors caused by fatigue, the total trial time per day for each participant did not exceed 2 hours. However, for parts that required repeated trials, the test cycle might be extended. The participants were well informed with the experiment purpose, procedures, and how their data would be used, all of which were explained and clarified in an information sheet. The participants agreed to take part by signing up the included consent form. The whole study plan was approved through the University Ethics Committee established in the Xi'an Jiaotong-Liverpool University.

### Section 4.2.1 Apparatus and Display

The aim of the research is to study how user perceive material appearance in an immersive viewing environment, which is often constructed and rendered with a real-time visualisation engine. Unreal Engine (UE4) was used to present the rendered materials to the viewer. UE4 has a good rendering performance across the traditional 2D and the stereoscopic VR viewing modes (Jacobson & Lewis, 2005).

• Devices Details: In terms of VR viewing mode, this study used the headset, HTC Vive Pro. As for the traditional 2D viewing mode, the image stimuli were presented one at a time on a calibrated 4.5Ghz gaming laptop Alienware AREA-51 M with 17-inch. The resolution of the VR device is 2800× 1600 pixels, and the resolution of the laptop is 1920 × 1080 pixels.

• Visual Distance and Size: this study provided a uniform display view (including lighting and environment) on two different viewing modes (VR and laptop) so that the participants could equally identify all parts of the display space when viewing any device image. The viewing distance was set to 850 mm, and the image and display size was 1669 pixels by 736 pixels in the two-viewing mode.

• Field of View: Fulvio & Rokers (2017) found that there was no significant difference in perceptual accuracy between active and fixed VR environments, though the jittering of head movements did not significantly improve perceptual accuracy. Therefore, in the experiment, this study did not specifically use head-fixed VR environments. The distance between the camera and the workpiece was about 350 mm, and the valid field of view had a width of around 520 mm.

• Material Parameters: this study focused on the material perception resulting from the changes of properties in synthesized material models, i.e., BRDF-based models. To reduce confounding effects, this study excluded other factors such as texture maps that may influence the material appearance. In addition, Fleming *et al*. (2003) proposed to use ambient lighting to improve material discrimination. So, the model was directly placed in the scene and lit with the default skylight and environment map in UE4. The present study utilized the physically based rendering (PBR) editing feature in UE4 to define the variation of material parameters. UE4 has PBR as the main shading method, which mainly affects shader, lighting, and other display effects (Shen *et al*., 2022).

BRDF model is designed to describe the relationship between PBR material and light, and to achieve the lighting calculation process (Zhou *et al.*, 2022). Metal and plastic were selected as the test materials, which were usually the base surface appearance generated with BRDF-based reflectance models. The editing of materials only involves the addition of colour and roughness or specularity. In addition, metal materials attach metallic instruction. Because the experiment is to test the change of material properties, the components used in UE4 for PBR include base colour, roughness, metallic and specular. Based on the function of material editing in UE4, this study chose to vary the levels of three material properties, which were the roughness of metal, the roughness of plastic, and the specularity of plastic. The material parameters under these three test properties are shown in Table 4.1, where the symbol "/" represents the test property.

*Table 4.1. The material parameters under metal-roughness, plastic-roughness, and plastic-specularity.*

| | Colour | | | Metallic | Roughness | Specular |
|---|---|---|---|---|---|---|
| | R | G | B | | | |
| Metal-Roughness | 0.7 | 0.5 | 0.03 | 1 | / | - |
| Plastic-Roughness | 0.2 | 0.1 | 0.1 | - | / | 0.45 |
| Plastic-Specularity | 0.2 | 0.1 | 0.1 | - | 0.28 | / |

Since the material properties in this study refer to the parameters of material visualisation in the rendering engine, the functions based on the material properties in UE4 are explained as follows:

- Roughness: in the field of mechanical design, material roughness is defined as the micro geometric shape formed by the finished surface. Different from this, in UE4, roughness represents the behaviour of light contacting the object surface, that is, the smoothness of the object. Roughness parameter 0 is specular reflection, while roughness 1 is completely matte or completely diffuse.

- Specularity: specular used to control the amount of specularity of non-metallic surfaces.

## Section 4.2.2 Stimuli

### *Study 1: The operational perceptual scale*

In order to understand the users' perceived differences of material appearance in the settings, the research established an operational perceptual scale of the rendered visual stimuli. The scale served as the basis to evaluate viewer performances in later experiments. This study used the Method of Adjustment (MoA), which is a psychophysical procedure to measure the threshold for the human to recognize the difference between two levels of a physical stimulus (Stevens, 1946). MoA repeats the task in multiple trials. The difference between the correct stimulus level and the user response is recorded, and the average value is taken in all trials as a measure of perceived sensitivity (Elliott, 2021). As described in earlier sections, the roughness and specularity of the two selected materials were to be evaluated. Unlike typical psychological experiments that require a substantial number of participants, psychophysics methods often require less many and trained observers (in some cases, 1 ~ 2) to perform a substantial number of trials to support a statistically sound analysis (Read, 2015). The rationale is that psychophysics methods often test on human physiological capabilities, which are less likely to be confounded by subjective factors such as personality traits or cultural profiles. According to Meyer & Shinar (1992), the background of the observer does not seem to affect the basic perception evaluation, because the results are largely independent of the participants' familiarity with statistics. In this case, an observer was recruited and trained to perform the trials in this part of the study.

For each trial, the participant identified the Just Noticeable Differences (JND) of material property (roughness and specularity) using the Method of Adjustment. JND refers to the minimum visibility threshold of the human visual system, which accounts for the difference between two stimuli intensities that the participant is able to detect (Liu *et al*., 2010). In other words, it is the minimum change threshold that an observer can observe from one material property value to the next threshold. The roughness and specularity parameters in UE4 can be varied within 0 ~ 1, between which the material properties increase as the number goes up. The test process is shown in Figure 4.2. During the test, the material properties viewed by participants were displayed on the computer screen. The participants were then required to drag the material parameter slider with the mouse to adjust the value of material properties. The participant began to adjust from the starting point till the first JND, where the participant could clearly see the changes in material properties. Using that JND increment as the new reference, he then continued to adjust the roughness till the next JND was identified. This procedure was performed recursively, and the whole adjustment process would be completed when reaching the other end of the roughness value. To avoid the habitual and expectance errors, this test balanced the trial sequence by asking the participant to start the adjustment from 0 to 1 and 1 to 0 alternatively. When adjusting the roughness and specularity in UE4, the displayed values of the material parameters were made invisible to the participant, so he could only identify the change based on visual judgments. The test scenes used in the experiment are shown in Figure 4.3. The other material properties, such as colours, remained unchanged as the control factors.

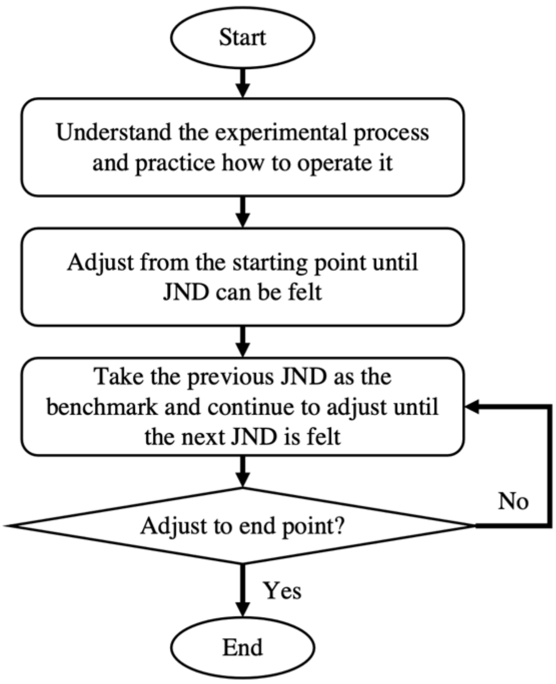


*Figure 4.2. The test process of the Method of Adjustment for testing the perceptual scale.*

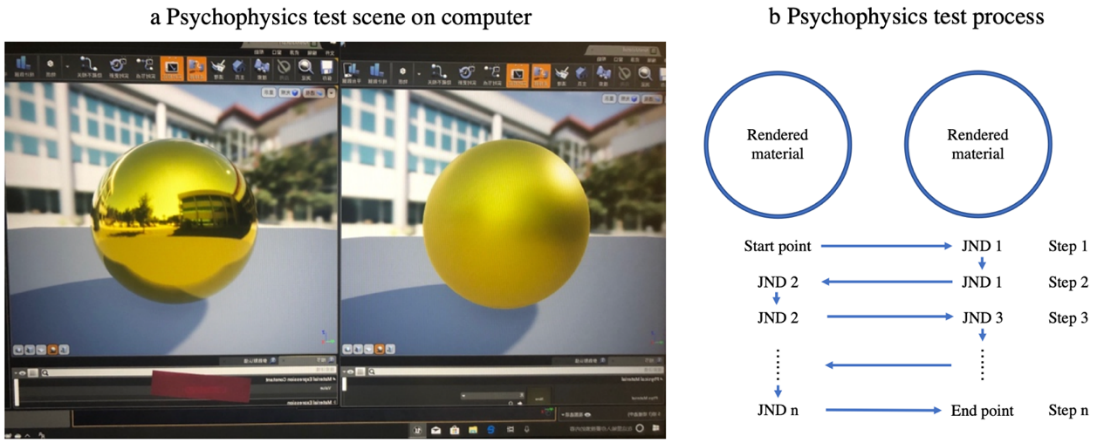


*Figure 4.3. The test scenes are used for the psychophysics experiment.*

In order to increase the reliability of the result, the adjustment process was repeated by the participant 20 times for the three material properties. The number of adjustment steps performed by the participant was then considered as the perceptual scale of physical stimulus change. To aggregate the accountable number of steps across these many adjustment processes, this test eliminated those steps, i.e., JNDs, which appeared less than 20% in all adjustment processes. In our case, in the range of the material parameters (0 ~ 1), the participant could clearly perceive 19 times of appearance changes on the three materials properties (the roughness changes of metal, the roughness and specularity changes of plastic). That, the participant had performed 19 adjustment steps, which resulted in 19 in-process JNDs, in each adjustment process. Then, for each material parameter, a total of 380 (with 20 adjustments processes and 19 adjustments for each of the processes) trials were performed by the participant. The 20 sets of in-process JND values were then averaged to obtain the final JNDs. The material samples with the 19 final JNDs of material properties are shown in Figure 4.4.

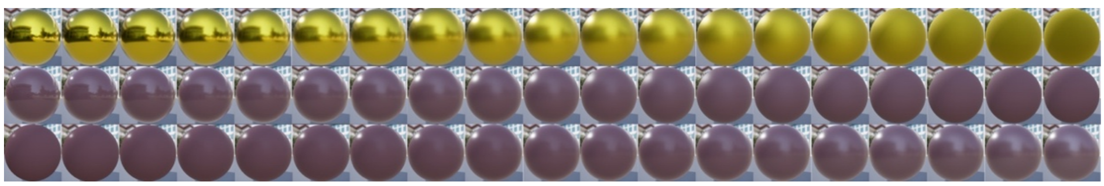

*Figure 4.4. The material samples with the 19 final JNDs of material properties. a: the first row shows the perceived JNDs of metal-roughness; b: the second row shows the perceived JNDs of plastic-roughness; c: and the third row shows the perceived JNDs of plastic-specularity.*

At the same time, according to the accepted 19's JND values, this study graphed the stimulus–response curves to verify the perceptual scale. With JND values as the y coordinates and the adjustment steps (19 steps) as the x coordinates, the curves can be plotted to show the trends of the perceived appearance changes against material parameter changes. This study used the statistical analysis software, SPSS, to graph the curves. As shown in Figure 4.5, the discrete points represent the test values, the fitted curves are drawn in solid, and the S curves are dotted. The logarithm relationship (S-curve) indicates that the scale measured by the experiment conforms to Weber's law (Fechner *et al.*, 1966), which states that perceivable differences in physical properties are a fixed proportion of their size. This supports the hypothesis that viewer cannot perceive the linear changes in numerical values that set the material properties.

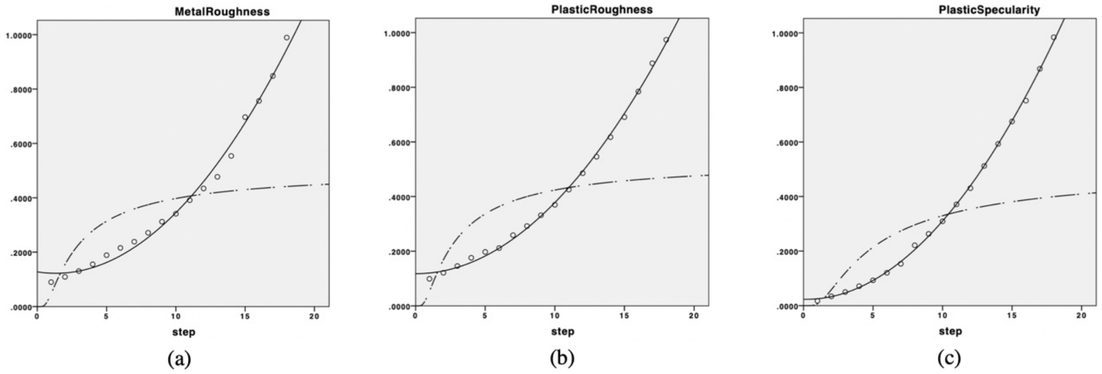


*Figure 4.5. The charts were generated based on the test results. a: the left chart represents the viewer's responses to the changes of metal-roughness; b: the middle one represents those to the changes of plastic-roughness; c: the right chart represents those to the changes to plastic-specularity.*

### *Study 2: Test material selection*

In the above experiment, this research established the perceptual scale for the material appearance generated by the rendering engine used in this study. The scale was to be used as the measurement reference that allowed us to compare the participants' performance in VR and traditional viewing mode. Furthermore, the research doubled the measurement units by inserting an intimidate value (averages) between each succeeding pair of the JNDs. In the case of 19 JNDs, 38 measurement unit values were generated. One may relate this treatment to the Sampling theory (Rao, 1973), in which the samplings are often doubled to ensure a good coverage of continuous signals. Therefore, in order to generate three groups of varied material stimuli: metal-roughness, plastic-roughness, and plastic-specularity, the study prepared three sets of 38 synthesized materials with the corresponding JND and intermediate values as the parameters. The generated material samples were then applied to the test spheres to render 38 images to be viewed on the 2D viewing mode, as well as the 38 stereoscopic pairs to be viewed in VR mode.

The aim of the study is to investigate how a viewer identifies the changes of material appearances under the two viewing conditions. This test firstly needed to select the reference materials to be compared against the changes of material properties of the test materials. Despite that a viewer is able to identify quantifiable nuances in the changes of material property, the research acknowledges the fact that humans often classify the materials with a qualitative and coarse description such as smooth or rough. Therefore, this study ran a qualitative sorting session to select the reference materials. This study recruited a total of 20 participants (19–30 years old, 10 males and 10 females) to observe the three clusters of test materials. The participants were asked to sort the material images within each cluster into three levels of quality:

• Level of metal-roughness: smooth, medium, and rough;

• Level of plastic-roughness: smooth, medium, and rough;

• Level of plastic-specularity: non-reflective, medium, reflective

By aggregating the participants' sorting results, the research obtained the three sub-clusters of each material image cluster. In each sub-cluster, one material image was randomly selected as the reference for later comparison tasks. In total, this study took 9 from the 114 material images as the reference materials (noted with Ref. 1, Ref. 2, Ref. 3, ..., Ref. 9).

### Section 4.2.3 Participants

A total of 12 participants (n = 12) were recruited for the experiment, with 7 males and 5 females. Participants were aged between 20 and 31 years old (M = 21.4, SD = 3.12). The participant was randomly recruited from Xi'an Jiaotong- Liverpool University. Gender is not considered as the influencing factor (Thaler *et al.*, 2018), because this study is not related to the measurement of subjective factors such as material aesthetics.

### Section 4.2.4 Procedure

This experiment evaluated the accuracy and precision of the participants' judgments of material appearances under the two viewing conditions. This study used within-subject design, i.e., each participant performed the same judgment tasks in both 2D and VR viewing conditions. The reference materials and the test materials were placed in parallel in the rendered view, as shown in Figure 4.6. The reference material was placed on the left. The material sample on the right was to be changed by the participant for selecting the one that they deemed as a match to the reference material. The lighting of the scene was controlled and remained the same to avoid the influence of illumination changes on the material appearance. The interface setting of 2D mode and VR was exactly the same. The participants continuously switched the test materials and compared them against the reference till they found the match. (Under the VR viewing condition, the participants switched the test materials with the left and right keys of the controller. Under the 2D viewing condition, the participants switched with the left and right arrow keys of the laptop's keyboard.) The test process is illustrated in Figure 4.7. In order to prevent habitual and expectation errors, the sequence of the test materials was randomized. For each reference material, each participant was required to per- form ten times of finding the matching material on the right. The same procedure was repeated in the two viewing environments. There were nine reference materials, 10 matching attempts for each of them, and two viewing conditions. As a result, each participant performed a total of 180 (9 × 10 × 2) trials for the matching experiment. To avoid the experimental errors caused by fatigue, the participants were allowed to take breaks among trials.

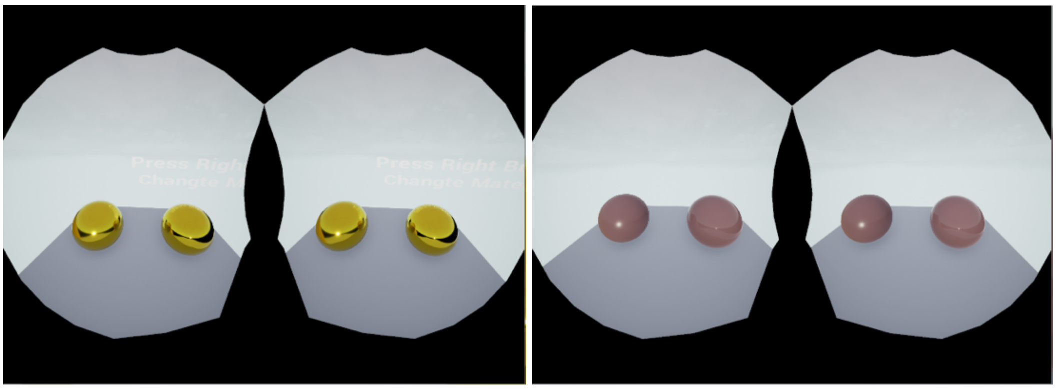

*Figure 4.6. The test scene of the reference object and the test object.*

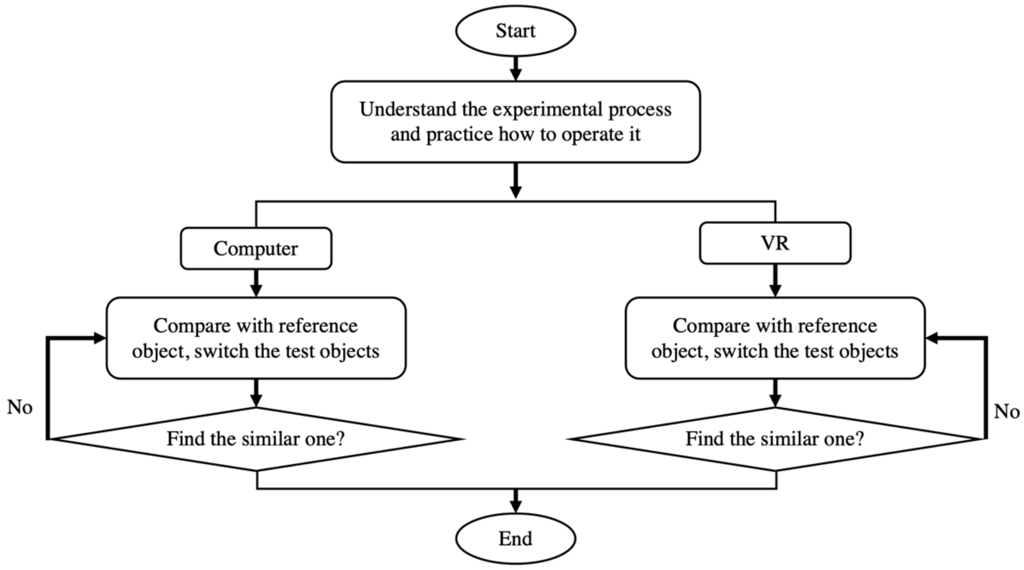


*Figure 4.7. The test process of the comparative trials.*

## Section 4.3 Results

Synthesized surface materials are an essential visualisation element to represent and simulate the appearances of virtual objects such as product prototypes. In this chapter, the research investigated whether the perception of rendered surface materials would be different between a 3D immersive/VR viewing condition and a traditional 2D one. For rendered surface materials, roughness and specularity are the two major parameters that modulate the rendering outcome. This study varies the two parameters and incorporate psychophysics techniques to derive a scale for measuring the perceivable changes of material appearance. Using the perceptual scale as the basis, the study run a series of surface appearance matching tasks and compare the participants' task performances in the VR viewing mode and the 2D viewing mode.

This research considered two aspects, precision and accuracy, when measuring the participants' performance of judging material appearances in VR and traditional 2D viewing modes. When a participant selected the exact matching material sample against the reference material, it was considered as a "correct hit," i.e., the two materials had exactly the same roughness values. Accuracy thus refers to the probability of the participants selecting out the exact match. This was calculated by averaging the correct hit rates across all participants. Precision, on the other hand, refers to the differences in material property values between the selected materials the reference materials.

To analyse the accuracy, the Chi-square test is used to compare the statistical differences of the performances under the two viewing conditions. Chi-square test is a nonparametric method that can provide information about the significance of any observed differences in categorical data (McHugh, 2013).

For precision, factor analysis of variance (F-ANOVA) is used to determine whether the individual and interaction of each factor are statistically significant (Collin *et al.*, 2014) in changing the users' perception of the material appearances. If the statistical p value is less than 0.05, the factors are considered to be significantly causing differences in the participants' performances on the material matching task.

### Section 4.3.1 Metal Roughness

In Figure 4.8, the participants' performances corresponding to each of the three reference materials in the metal roughness test are marked on the horizontal axis (Ref 1, Ref 2, and Ref 3), and the average accuracy is noted on the vertical axis. The blue bars represent the accuracy under the 2D viewing condition, and the green bars represent that under the VR viewing condition. In the accuracy test, the more the participants choose the matching material, the higher the final result will be. As shown in the figure, under the test results of the three reference materials, the green bars are generally higher than the blue bars, which indicates that the participants perform better (10% ~ 20% more accuracy) in VR as compared to 2D. Table 4.2 shows the results of the Chi-square tests. From the cross-tabulation, the number of correct choices in VR is higher with a statistical significance than that in 2D [for Ref 1, $\chi^2$ (1, N = 240) = 16.875, $p < .001$; for Ref 2, $\chi^2$ (1, N = 240) = 6.759, $p = .009$; for Ref 3, $\chi^2$ (1, N = 240) = 4.429, $p = .035$]. Considering the case of Ref 3, the performance difference between the VR viewing condition and 2D viewing condition is the smallest among the three reference materials, but the participants still get 15 more correct hits in VR as compared to 2D. The biggest difference is Ref 1. The participants in VR get 30 more correct hits than those in 2D, and the number of selection errors in VR is the least among the three groups, only making 25 incorrect hits in the 120 trials.

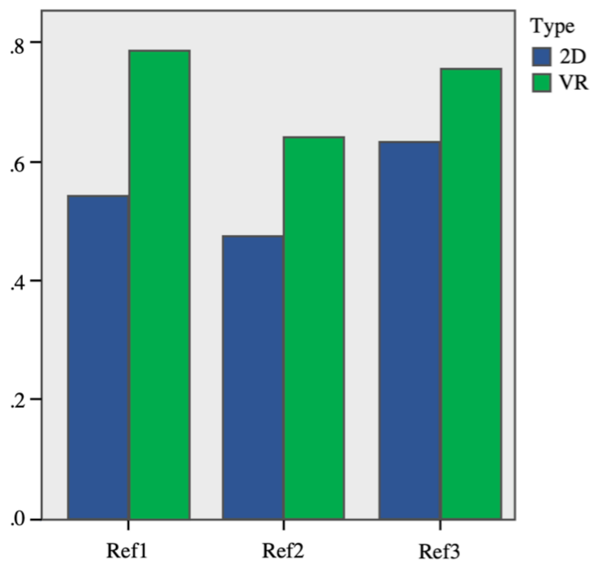


*Figure 4.8. Mean accuracy results of the reference objects judgment based on three metal-roughness (MR) degrees.*

*Table 4.2. The Chi-square tests results for Ref 1, Ref 2 and Ref 3 of metal-roughness (MR).*

| | | Ref 1 | | | Ref 2 | | | Ref 3 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 2D | VR | Total | 2D | VR | Total | 2D | VR | Total |
| Count | Wrong | 55 | 25 | 80 | 63 | 43 | 106 | 81 | 59 | 140 |
| | Right | 65 | 95 | 160 | 57 | 77 | 134 | 76 | 91 | 167 |
| | Total | 120 | 120 | 240 | 120 | 120 | 240 | 120 | 120 | 240 |

| | | Value | df | Sig. | Value | df | Sig. | Value | df | Sig. |
|---|---|---|---|---|---|---|---|---|---|---|
| Chi-Square Tests | Pearson | 16.875[a] | 1 | <.001 | 6.759[a] | 1 | .009 | 4.429[a] | 1 | .035 |
| | N of Valid Cases | 240 | | | 240 | | | 240 | | |

The result of the precision analysis is shown in Table 4.3. The viewing conditions (VR vs. 2D) and the reference materials are the factors that have a statistically significant impact on the participants' judgments, $F (1, 714) = 44.528$, $p < .001$. The main effects of the experimental factors can be seen more clearly in Figure 4.9 The horizontal axis represents the three levels of reference material (Ref 1, Ref 2, and Ref 3), while the averages of precision are marked on the vertical axis. Similarly, the blue line represents the precision under the 2D viewing condition and the green line represents the precision under the VR viewing condition. First of all, the figure shows that the precision of the metal-roughness judgment of participants is different between the two viewing conditions. Moreover, the precision also manifests differently at the three levels of reference material. There are no interactional effects between the viewing condition and the reference material. In the precision test, since the deviation value of the test result is averaged, the smaller value represents the higher precision performed by the user in this viewing mode. In comparison with viewing in 2D condition, the participants performed with a narrower range of errors, i.e., higher precision in VR condition. For example, the precision value of Ref 1: The participants make the least error in the VR viewing condition ($n = 120$, $M = .208$, $SD = .4078$), while the error value in the 2D viewing condition is higher ($n = 120$, $M = .467$, $SD = .5175$). On the other hand, the participants seem to perform less well when the reference material is at the medium level (Ref 2) of roughness, the precision value of VR condition ($n = 120$, $M = .367$, $SD = .5010$) is lower than the 2D condition ($n = 120$, $M = .775$, SD

= .8931). And the analysed results for Ref 3 is same, with lower scores in the VR condition (n = 120, M = .242, SD = .4299) as compared to the 2D condition (n = 120, M = .458, SD = .6597). This nonetheless supports Weber's law in that median fluctuations are more obvious in a similar type of psychophysical test.

*Table 4.3. The ANOVA results and descriptive statistics for metal-roughness (MR).*

| Variable | Mean | SD | n |
|---|---|---|---|
| Ref 1 | | | |
| 2D | .467 | .5175 | 120 |
| VR | .208 | .4078 | 120 |
| Ref 2 | | | |
| 2D | .775 | .8931 | 120 |
| VR | .367 | .5010 | 120 |
| Ref 3 | | | |
| 2D | .458 | .6597 | 120 |
| VR | .242 | .4299 | 120 |
| Source | df | F | *P* value |
| Viewing Modes | 1 | 44.528 | <.001* |
| Reference | 2 | 11.798 | <.001* |
| Error | 714 | | |

*Significant difference at α = .05

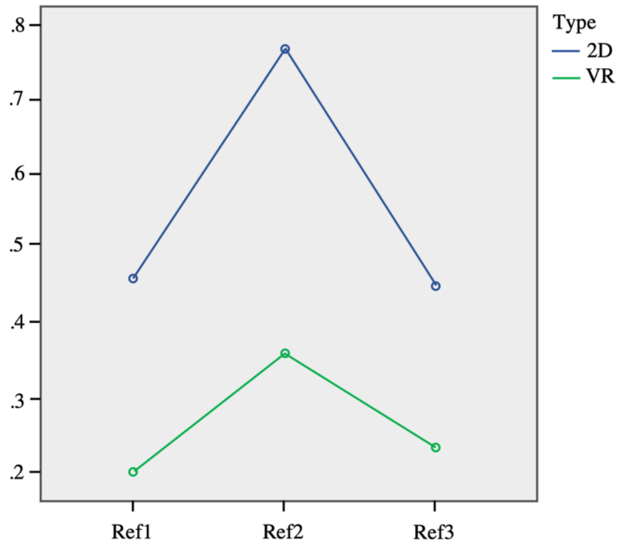


*Figure 4.9. The mean result of the precision analysis on the metal-roughness (MR) according to the three reference objects.*

### Section 4.3.2 Plastic Roughness

One can see from Figure 4.10 that the participants perform with higher accuracy in VR. This is also confirmed by the summary of the data in Table 4.4. Among the results of Ref 1 and Ref 2, the difference between the test results of the two viewing conditions is relatively stable, and the accuracy value is also very close. However, the correct hits in VR (84 times and 82 times) are still more than those in 2D (61 times and 66 times). Ref 3 produces the lowest accuracy in VR (60 correct hits), which is still better than 2D (42 correct hits). That is to say, the participants have a greater possibility to pick the exact match through VR viewing. The Chi-square test is shown in Table 4.3. The result statistically supports this difference in their performances [for Ref 1, $\chi^2$ (1, N = 240) = 9.217, p = .002; for Ref 2, $\chi^2$ (1, N = 240) = 4.512, p = .034; for Ref 3, $\chi^2$ (1, N = 240) = 5.524, p = .019].

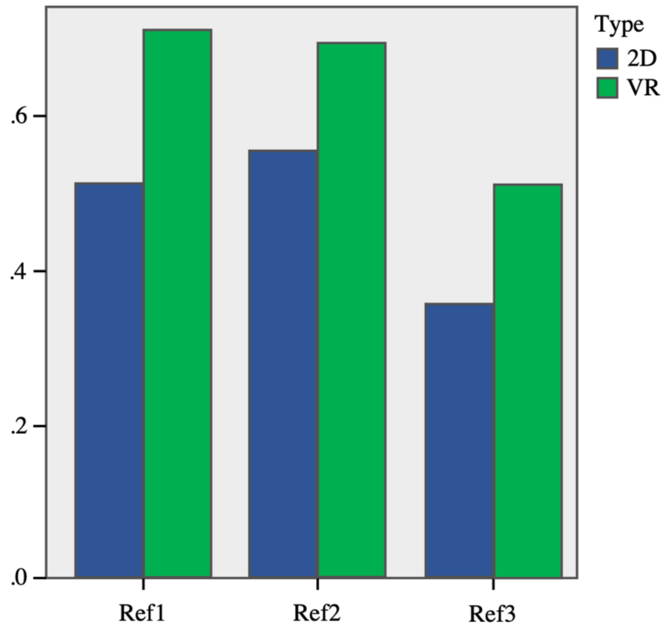


*Figure 4.10. Mean accuracy results of the reference objects judgment based on three plastic-roughness (PR) degrees.*

*Table 4.4. The Chi-square tests results for Ref 1, Ref 2 and Ref 3 of plastic-roughness (PR).*

| | | Ref 1 | | | Ref 2 | | | Ref 3 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 2D | VR | Total | 2D | VR | Total | 2D | VR | Total |
| Count | Wrong | 59 | 36 | 95 | 54 | 38 | 92 | 78 | 60 | 138 |
| | Right | 61 | 84 | 145 | 66 | 82 | 148 | 42 | 60 | 102 |
| | Total | 120 | 120 | 240 | 120 | 120 | 240 | 120 | 120 | 240 |

| | | Value | df | Sig. | Value | df | Sig. | Value | df | Sig. |
|---|---|---|---|---|---|---|---|---|---|---|
| Chi-Square Tests | Pearson | 9.217[a] | 1 | .002 | 4.512[a] | 1 | .034 | 5.524[a] | 1 | .019 |
| | N of Valid Cases | 240 | | | 240 | | | 240 | | |

In terms of precision, both the reference material (with varying levels of roughness) [F (2, 714) = 33.218, p < .001] and the viewing condition [F (1, 714) = 21.366, p < .001] contribute to invoking significantly different responses on the perceived roughness. This result is shown in Table 4.5. The mean precision plots are shown in Figure 4.11. For Ref 1 and Ref 2, the precision results of VR condition are very close [Ref 1: (n = 120, M = .317, SD = .5018); Ref 2: (n = 120, M = .317, SD = .4671)]. For Ref 2, the error value of 2D condition (n = 120, M = .525, SD = .6346) is the lowest in the plastic-roughness test, which is still larger than the error result produced under VR.

*Table 4.5. The ANOVA results and descriptive statistics for plastic-roughness (PR).*

| Variable | Mean | SD | n |
|---|---|---|---|
| Ref 1 | | | |
| 2D | .592 | .7159 | 120 |
| VR | .317 | .5018 | 120 |
| Ref 2 | | | |
| 2D | .525 | .6346 | 120 |
| VR | .317 | .4671 | 120 |
| Ref 3 | | | |
| 2D | 1.075 | 1.1013 | 120 |
| VR | .775 | .9209 | 120 |
| **Source** | **df** | **F** | ***P* value** |
| Viewing Modes | 1 | 21.366 | <.001* |
| Reference | 2 | 33.218 | <.001* |
| Error | 714 | | |

*Significant difference at α = .05

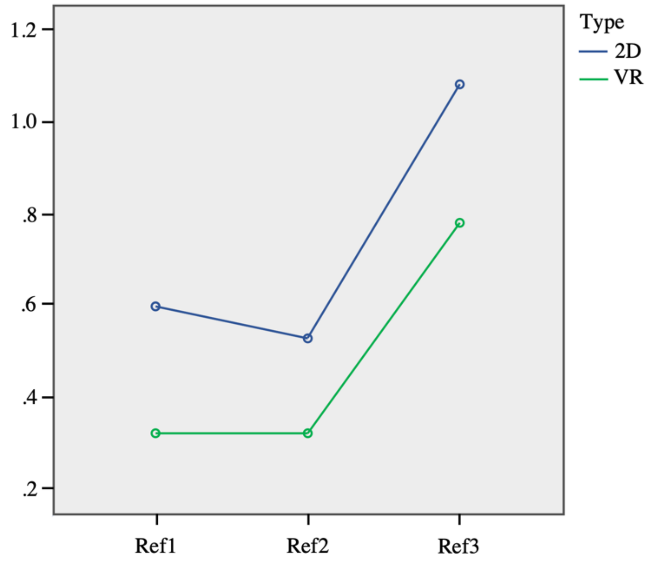


*Figure 4.11. The mean result of the precision analysis on the plastic-roughness (PR) according to the three reference objects.*

One notable finding is that for plastic materials, high roughness (Ref 3) is more likely to cause judgment errors than the other two levels. In this case, the precision difference of VR value (n = 120, M = .775, SD = .9209) and 2D value (n = 120, M = 1.075, SD = 1.1013) is large. Moreover, in the VR viewing condition, the participants make the least error approximate 0.2 in judging at the medium level of roughness. The trend is seemingly opposite from what has been observed in their judgments on metal-roughness, for which the participants made the most error at the medium level.

### Section 4.3.3 Plastic Specularity

Figure 4.12 shows that under VR viewing condition, the participants perform with higher accuracy when selecting the exact match of specularity. Taking the test results of high specularity (Ref 3) as an example, it can be seen that the correct hits in both VR and 2D are the lowest, 61 and 39, respectively. The Chi-square test and the cross-tabulation, which are shown in Table 4.6, confirm that the difference in the performances under the two viewing conditions is statistically significant [for Ref 1, $\chi^2$ (1, N = 240) = 6.669, p = .010; for Ref 2, $\chi^2$ (1, N = 240) = 8.832, p = .010; for Ref 3, $\chi^2$ (1, N = 240) = 8.297, p = .010].

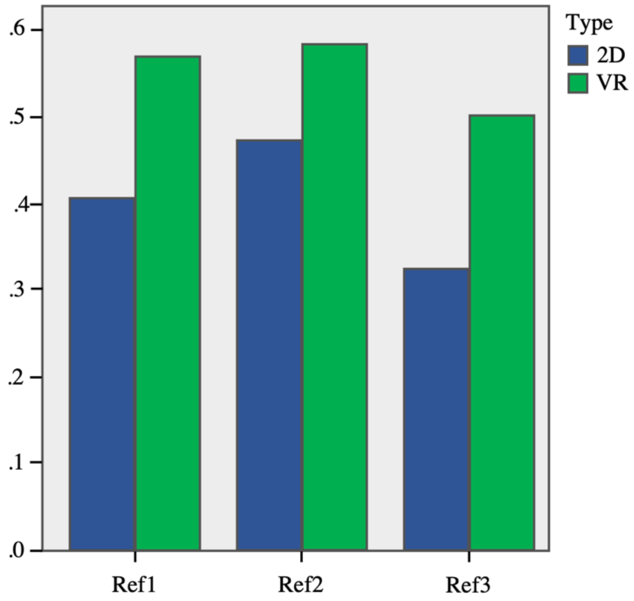


*Figure 4.12. Mean precision results of the reference objects judgment based on three plastic-specularity (PS) degrees.*

*Table 4.6. The Chi-square tests results for Ref 1, Ref 2 and Ref 3 of plastic-specularity (PS).*

| | | Ref 1 | | | Ref 2 | | | Ref 3 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 2D | VR | Total | 2D | VR | Total | 2D | VR | Total |
| Count | Wrong | 71 | 51 | 122 | 69 | 46 | 115 | 81 | 59 | 140 |
| | Right | 49 | 69 | 118 | 51 | 74 | 125 | 39 | 61 | 100 |
| | Total | 120 | 120 | 240 | 120 | 120 | 240 | 120 | 120 | 240 |

| | | Value | df | Sig. | Value | df | Sig. | Value | df | Sig. |
|---|---|---|---|---|---|---|---|---|---|---|
| Chi-Square Tests | Pearson | 6.669[a] | 1 | .010 | 8.832[a] | 1 | .010 | 8.297[a] | 1 | .010 |
| | N of Valid Cases | 240 | | | 240 | | | 240 | | |

In terms of precision, similarly, the performance on plastic-specularity is significantly influenced by the viewing condition [F (1, 714) = 11.655, p < .001] and the reference material [F (2, 714) = 30.427, p < .001]. The result is shown in Table 4.7. Moreover, one can see from Figure 4.13 that participants made less error when viewing in VR. At low specularity (Ref 1), both VR viewing modes (n = 120, M = .4667, SD = .57880) and 2D viewing modes (n = 120, M = .6667, SD = .66526) have relatively higher precision. Nevertheless, for both viewing conditions, the errors become larger when the specularity increases. At high specularity (Ref 3), the error produced in the 2D viewing condition (n = 120, M = 1.1167, SD = 1.05467) is the largest. Although the participants perform better in VR at this specularity level, it still generates the least precision in terms of VR viewing conditions (n = 120, M = .6333, SD = .76623).

*Table 4.7. The ANOVA results and descriptive statistics for plastic-specularity (PS).*

| Variable | Mean | SD | n |
|---|---|---|---|
| Ref 1 | | | |
| 2D | .6667 | .66526 | 120 |
| VR | .4667 | .57880 | 120 |
| Ref 2 | | | |
| 2D | .7333 | .79635 | 120 |
| VR | .4750 | .62123 | 120 |
| Ref 3 | | | |
| 2D | 1.1167 | 1.05467 | 120 |
| VR | .6333 | .76623 | 120 |
| **Source** | **df** | **F** | ***P* value** |
| Viewing Modes | 1 | 11.655 | <.001* |
| Reference | 2 | 30.427 | <.001* |
| Error | 714 | | |

*Significant difference at $\alpha = .05$

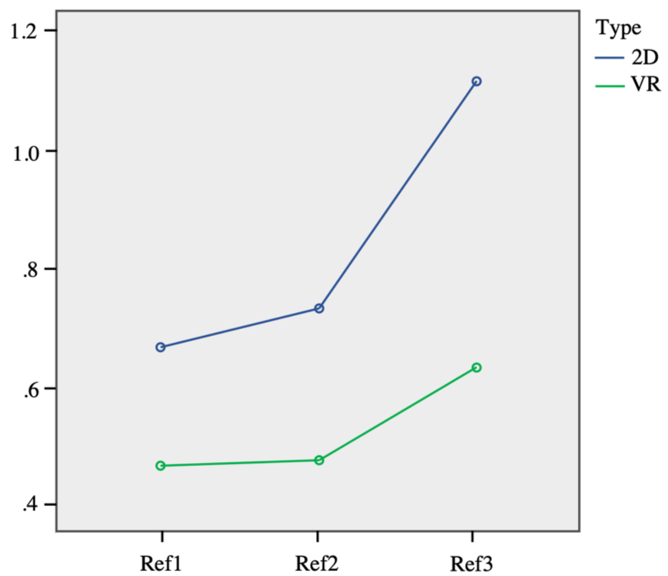


*Figure 4.13. The mean result of the precision analysis on the plastic-specularity (PS) according to the three reference objects.*

## Section 4.4 Discussion

This study aims to investigate the perceptual difference of rendered materials between the immersive VR viewing mode and the traditional 2D viewing mode. Based on the results, the VR viewing condition allows the participants to make more correct hits and less error in judging material properties. This supports the previous research done by Gourishetti & Manivannan (2019), which argued that VR provided less visual noise than non-immersive environments and helped participants make more focused judgments and choices. In terms of judging specific materials, there are differences between evaluating metal properties and plastic properties. This study has found that the changes in accuracy and precision performances on metal-roughness exhibit the patterns similar to the response curves generated at the initial psychophysical test. A hypothetical explanation is that apart from the composited ones, most metal materials come from the natural world. We as the human beings might have evolved with an innate ability to recognize the differences in metal properties. Plastic materials, on the other hand, appeared much later in human history. Human beings may need to be trained to tell the minute differences among plastic materials. However, this is an extended hypothesis out of the scope of this study.

The sphere was selected as the test object to present synthetic materials in this study for it was widely used in previous experimental works (Filipet *et al.*, 2008; Jarabo *et al.*, 2014; Kerr & Pellacini, 2010; Sun *et al.*, 2017). In an earlier exploratory experiment on the influence of object shape on BRDF-based visualisation, Vangorp *et al.* (2007) studied various effects on material discrimination in the natural environment and found the material types playing a stronger role than shapes in discerning material appearances. Subsequent studies have also given strong evidence that material perception mainly depends on the cues of lightning position or material type (TE PAS & Pont, 2005; Khang *et al.*, 2006; Schlüter & Faul, 2019). Filip *et al.* (2008) believed that the conclusion that "sphere is not suitable for material recognition task" should not be presumably extended to the evaluation of other material rendering functions. Other studies chose test objects with complex shapes and structures for investigating specifically how the curvature of object shapes and lighting conditions affect the users' judgment (Vanhoey *et al.*, 2017; Lagunas *et al.*, 2021). Moreover, most of the test scenarios in these studies were presented on the traditional 2D displays. Whether the findings are applicable in immersive VR environments remains an agenda for further studies. Nevertheless, this study consider that object shape comparison would be meaningful when synthetic materials are attached to specific product models.

Another limitation of the study is related to the effect of colours. Indeed, colours can be treated as either an intrinsic or extrinsic property of certain materials, henceforth influencing the visual recognition of material types. For example, many previous studies have shown that colour and translucency affect the perceived glossiness (Gigilashvili *et al.*, 2019; Honson *et al.*, 2020). In this case, colour as an intrinsic property may decide whether a glossy material is perceived as metal or shiny plastic. This study focused primarily on the perceptual differences in material appearances in traditional 2D and VR viewing conditions. In our case, this study took the control approach and set the colour to correspond well to a users' common impression of material appearance. For example, yellow/gold was chosen to represent the metal material and remained unchanged across all trials on viewing the metals. On the other hand, the colours of plastic-type materials could be very diverse so this study used those provided by default in the rendering engine. Therefore, colours were controlled within each material category but not compared across all material types. On that basis, the findings show that the difference in material properties significantly affects the participants' performances. Moreover, a few studies have discussed the influence of colours on depth perception (Singh *et al.*, 2018; Do *et al.*, 2020; Erickson *et al.*, 2020; Hertel & Steinicke, 2021). One key difference between VR and 2D is the stereoscopic depth effect produced by VR. The interactive effects between colours and the stereo depth cue are of the interest to investigate in future work.

## Section 4.5 Summary

This chapter discusses the users' ability to identify material properties in virtual environment. Material perception in the immersive environment is an interesting and under-investigated topic. On the other hand, a realistic simulation of material appearance plays a crucial role in evaluating design concepts such as those for developing a product. As more studies introduced immersive viewing approaches to product evaluation, the research questions raised in this study became more relevant. The research in this chapter studied how may the stereoscopic and immersive viewing experience influence our perception of synthesized surface materials. Using a real-time rendering engine, this study carried out a series of experiments under 2D and VR viewing conditions. Metal-roughness, plastic-roughness, and plastic-specularity were selected as the test material properties. This research started by establishing the perceptual scale of material appearance with psychophysical techniques. The perceptual scale was then used as a measurement mean to evaluate the participants' performances on judging material appearances in 2D and VR viewing conditions. The results lead to several valuable findings. In short, immersive viewing in VR allows the participants to identify material changes with higher accuracy and precision. This coincides with findings in previous psychophysical research: VR viewing condition can eliminate some visual noise and help users better experience and perceive virtual objects. Indeed, the stereoscopic and immersive effects may add further visual cues for us to deduce material appearances in a VR environment.

The perceptual scale also provides an important sight for designing the interface for material properties manipulation in 3D software, in which a perceptually valid scaling mechanism may be adapted, instead of the current uniform one. Another interesting phenomenon is that the participants have different response patterns between judging metal appearances and judging plastic appearances. This research suggested an evolution-based hypothesis for the interested researchers to explore further.

Based on these results, this study learned that the immersive experience of VR can provide users with more visual cues. In the VR viewing mode, the participants identify the matching materials at higher levels of accuracy and precision. These findings show that the depth impression in immersive viewing environments may result in a different perceptual response to the rendered surface materials. Therefore, in the next stage, the aim is to compare the recognition of material properties in VR and 2D viewing modes. By establishing a perceptual scale based on VR according to psychophysics, so as to compare it with the perceptual scale on the 2D viewing modes. In addition, texture, as one of the manifestations of materials, enables users to judge the category and characteristics of materials. Texture mapping is often used in design activities to enrich the visual effects of materials. In the next chapter, texture mapping as an influencing factor of material perception also be considered in VR environment.

# Chapter 5 Effects of Texture and Display Equipment on Recognition of Material Properties

## Section 5.1 Introduction

The matching task described in the previous chapter compared the users' judgement of material properties under the two viewing modes. In this chapter, this study specifically compares the users' recognition of roughness in VR and traditional 2D viewing modes, and consider the effect of texture mapping.

Each material has specific optical properties, and the way light is reflected along the surface materials will change, and the mode of this change varies with the materials. Furthermore, many materials (such as fabrics, trees, and leather) have specific natural textures characterized by regular in-completeness and random fluctuations (Komatsu & Goda, 2018). One can also regard the surface roughness as a special textural feature which is highly homogeneous and scatters the incident light uniformly in different directions. Different from the mechanical design, roughness is the change of the material surface caused by the processing technology. In the rendering engine, the roughness property is expressed as the reflection of the object's surface to the light. The representation of a texture mapping consists of a 2D texture map and a parameterised mesh with UV mapping, which maps the points on the shape manifold to the pixels in the texture mapping. This simulation process can be regarded as a method to control the reflection of the object's surface to the light and reconstruct the texture from a single image. Nowadays, the visual texture is often used for adding expressive and functional features to a product or its packaging. The texture, alongside shape and colour, is the primary design element to form the product's appearance (Tersiisky, 2004). Surface texture plays a role in enhancing or delivering product functions in the design process. Therefore, for designers, material texture affects product personality based on CMF design decisions (Ashby & Johnson, 2013). In this process, the visual texture is used in product simulation and development as a concrete representation of material visualisation (Shen *et al*., 2006), so the personalized display of surface materials is more convincing. Sener & Pedgley (2021) pointed out that visual texture can look realistic and convincing through viewing conditions. Users often associate visual texture with product detail and quality in design evaluation.

In the current design development, visualisation technology supports users to observe and understand the information, which depends on human perception and cognitive ability. Visual perception is generally considered the most reliable perceptual mechanism, which is often studied to explore and reveal the relationship between cognitive processes and visual information (Rensink, 2021). Historically, visual perception has been connected with visualisation technology to realize the design optimization based on the perception theory (Montello, 2002; Ware, 2019; Zacks & Franconeri, 2020). Similarly, vision is also the main sensations in VR. VR provides users with a strong sense of presence, utilizing our stereoscopic vision to present a vivid sense of depth. Slater (2018) indicated that users could be technically immersed in the virtual world by VR and made corresponding behaviours accordingly. As the thesis mentioned in previous sections, the 2D projection mode has been widely used (MacDonald *et al.*, 2008; Orsborn *et al.*, 2009; Kelly *et al.*, 2011; Lugo *et al.*, 2016; Valencia-Romero & Lugo, 2016). However, the depth and vergence cues of 3D representation help better understand subjects' perception (Pizlo, 2010; Higgins, 2012; Valencia-Romero & Lugo, 2017). The traditional design evaluation in 2D viewing mode mainly relies on simulating 3D digital models to verify the availability and visibility of VP (Deng & Wang, 2020). VR technology tried to transform the complex environment into a controllable virtual environment (Hettig *et al.*, 2018). This stereoscopic viewing condition also became a major factor producing different experiences between VR and traditional 2D viewing mode. Many studies have confirmed applicability and effectiveness of VR and applied it to the stage of product design, development, and evaluation. They stated that visual evaluation of VP reduces the prototyping cost and shortens the time-consuming design cycle, which benefits from the versatility and user-friendliness of VR technology (Bordegoni, 2011). As mentioned above, however, the device gap caused by HMD reminds users of the boundary between reality and virtual reality (Slater *et al.*, 2020). Material perception influenced by the binocular projection in VR technology has not received much attention, which may be one of the key factors to developing VR as a design evaluation tool.

The simulation of texture in rendering virtual product prototypes is thus important for a comprehensive design evaluation. The fineness of material textures provides supplementary depth information (El Jamiy & Marsh, 2019), which seems to interact with a VR immersive environment that provides enhanced depth perception. However, previous research on texture perception and material attributes focuses more on the induced tactile feedback but visual judgments, which usually drive design decisions. Filip & Haindl (2012) thought the appearance of real-world objects is significantly affected by the materials that override them. In particular, roughness can be recognized not only by touch but also by viewing the textural appearance. Therefore, the present study decided to solve the task of effective measurement and analysis of material attribute to reflect the real feelings of users in the design evaluation stage. Martin *et al.* (2017) pointed out that the design evaluation results are usually driven by the perceptual characteristics of materials, so the simulated effects of materials should not only reflect the texture and optical characteristics of materials, also capture the subjective feelings of users. However, the surface material perception on material properties and texture effect under different projection modes has not been fully understood. In the past few years, many studies have proposed many techniques and methods to measure the appearance of materials. However, Serrano *et al.* (2018) pointed out that editing and capturing data for material appearance is still a challenge. The controversial points of these studies are often based on different materials and material properties, so a measurable and quantitative perception dimension is very important.

### *Structure of the Chapter*

In this study, the psychophysics approach was used to respond to the following questions:

> *"Whether surface textures have an influence on the perceptual responses identified in those two viewing modes?"*

The research process thus involves establishing the perceptual scale of material attributes in VR viewing conditions through psychophysical methods and analyse the impact of surface textures on material perception in such an immersive viewing environment. The rest of this research is structured as follows: Related Works presented the current research in material perception, psychophysics, and VR in the field of design. In User Study, the research described the main content and test process of the comparative study. The data feedback measured through psychophysics is analysed in Results and discussed in Discussion. This research then conclude the work in Summary.

## Section 5.2 User Study

Presenting rendered surface materials involves visual perception, which leads to the results of VP evaluation. VR technology has been paid more attention in the research of design evaluation, which is inseparable from the feeling brought by stereo vision. Psychophysics plays a significant role to quantify users' response, because its emphasises the relationship between quantifiable physical stimuli and user awareness content (Liang & Acuna, 2020). This chapter experiment measures the difference threshold (Just-Noticeable Difference) of subjects' visual perception of material appearing in traditional 2D and VR viewing modes. The observer has the ability to distinguish the difference in stimulus intensity. Just Noticeable Difference (JND) provides a reliable minimum stimulus level that people can detect, allowing designers to reason about the amount of information conveyed. The experiment is divided into two parts to understand whether the surface texture will affect the perceptual changes of material properties.

### Section 5.2.1 Apparatus and Display

• Devices Details: The device that presents the scene for 2D viewing mode is the calibrated 4.5GHz gaming laptop Alienware AREA-51M, and the viewing device of VR is HTC Vive Pro.

• Visual Distance and Visual Size: The visual size observed by participants using two devices was fixed at 1920 * 1080 pixels, and the visual distance was set at 350mm.

• Field of View: Although the study informed participants to be as stable as possible when using VR devices, according to Fulvio & Rockers (2017), the jitter of users' heads when using HMD will not cause a significant difference. Therefore, this study did not specifically set a fixed HMD.

• Visual Scene: The 3D model was placed in the default scene of UE4 and illuminated with a fixed-point light source, skylight, and environment map. This setting is based on the suggestion of Fleming *et al*. (2003), that is, ambient lighting can improve the resolution of materials. VR and 2D modes present the same visual environment.

### Section 5.2.2 Stimuli

This study focused on the material perception resulting from the properties changes in synthesized material models. The virtual environment was generated using Unreal Engine 4 (UE4), and all 3D geometry and visualised materials were specially created for the scenario to ensure a consistent visual style. According to the set rules of the UE4 material editor, the roughness parameters can be varied in the range of 0 ~ 1, between which the material properties become rough with the increase of the value. This research measures the differences under the two viewing modes on the users' recognition between the materials with textured material or without textured, respectively, to reduce confounding effects. In the selection of test materials, the five most common materials for product design evaluation were selected based on Veelaert *et al*., (2020). They include two non-textured materials: metal and plastic and three textured materials: fabric, leather, and wood.

#### *Non-Textured Materials*

For the materials without texture elements, this study utilised the editing feature of physically-based rendering (PBR) in UE4 to define the variation of material parameters. Metal and plastic were selected as the test materials, which were usually the base surface appearance generated with BRDF-based reflectance models. As mentioned in section 4.2.1, the editing of materials only includes instructions on colour, metallic and specular. This study chose the material colour that does not cause confusion to users in daily life. For example, yellow/gold was chosen to represent the metal material and remained unchanged across all trials on viewing the metals. On the other hand, the colours of the plastic family are very diverse. On the material editing page of UE4, the parameters of non-textured materials are shown in Table 5.1. During the trial, only one material was attached to the sphere and placed in the centre of the field of view and as shown in Figure 5.1.

*Table 5.1. Parameter Settings for Metal and Plastic Material Editing in UE4.*

| | | Metal | Plastic |
|---|---|---|---|
| Colour | R | 0.7 | 0.2 |
| | G | 0.5 | 0.1 |
| | B | 0.03 | 0.1 |
| Metallic | | 1 | - |
| Specular | | - | 0.45 |

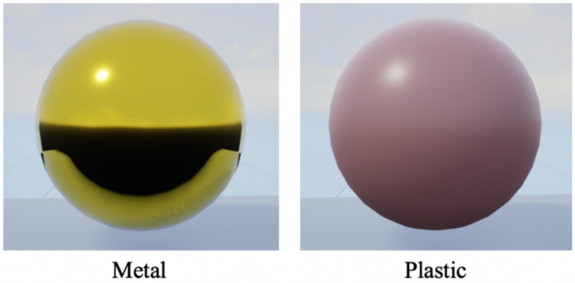


*Figure 5.1. The non-textured materials displayed in UE4.*

### *Textured Materials*

This study can recognize the object's material type, geometry, and surface texture through visual information when we observe an object. As the textured materials in this study, fabric, leather, and wood are also common in product design, which happens to be derived from their highly representative texture features. Texture mapping can enhance the realism of virtual objects, but sometimes the mapping process cannot ensure the integrity of the original image. There will be deformation, blur, and distortion (Sanchis Albert, 2019). As a material editing software, Substance Designer (SD) uses an algorithm to program the texture creation process, realizes texture effect superposition through Mask and Height Map, and stores 2D image data of all information in the form of node connection. The information can be generated by a node or transmitted from another node. This study utilized SD to simulate three textured materials. The fabric is designed as twill, the leather is tried to reflect the natural and irregular leather texture, and the wood grain is a transverse cutting pattern. In order to test the roughness perception of the selected materials for the further text, this study generated the texture mapping of materials in SD but did not edit and set the roughness parameters. These texture variables were then used in UE4 to modify the material in real-time after exposing them. The parameters of specific materials in SD are shown in Table 5.2, and the texture effect in UE4 is shown in Figure 5.2.

*Table 5.2. Parameter Settings for Fabric, Leather, and Wood Material Editing in SD.*

| | | Fabric | Leather | Wood |
|---|---|---|---|---|
| Colour | R | 99/75 | 91 | 204 |
| | G | 106/82 | 43 | 153 |
| | B | 114/100 | 20 | 95 |
| Technical Parameters | Luminosity | 0.5 | 0.5 | 0.5 |
| | Contrast | 0 | 0 | 0 |
| | Hue Shift | 0 | 0 | 0 |
| | Saturation | 0.5 | 0.5 | 0.5 |
| | Normal Intensity | 0.5 | - | 0.5 |
| | Normal Format | DirectX | DirectX | DirectX |
| | Height Range | 1 | 0.1 | 1 |
| | Height Position | 0.5 | 0.5 | 0.5 |
| | Ambient Occlusion Intensity | 0.5 | - | 0.5 |


*Figure 5.2. The textured materials displayed in UE4.*

## Section 5.2.3 Participants

Psychophysics has been committed to revealing the fundamental mechanisms common to all humanity, which are not affected by subjective factors such as participants' background, personality characteristics, or cultural level. There seem to be many individual differences or conflicting results in the field of binocular stereo vision, which does not seem to be caused by insufficient sampling of participants (Read, 2015). Given this hypothesis, psychophysical research tends to use a small number of subjects and long-term repetitive tests. Since the research content does not require the background or specialty of the participants, the participants were randomly recruited from the Xi'an Jiaotong-Liverpool University. Three participants (n = 3, 2 males and 1 female) participated in the study after informed consent and reported VR use experience. The participants aged between 24 and 29 (M = 26.3, SD = 2.52). The study was approved by the university ethics committee established by the XJTLU's organization.

### Section 5.2.4 Procedure

The test object of the research is the roughness change of the corresponding material. The setting of the virtual scene is shown in Figure 4.1, which shows the scene seen by the user in two viewing modes.

As for the typical psychophysical procedure, the Method of Adjustment (MOA) is suitable for the target task of continuous level measurement and can provide highly sensitive results according to the relatively few stimuli obtained by the subject's accurate sampling test (Elliott. 2021). In order to evaluate how the subjects distinguish the changes in material properties, this study used MoA to assess the participants' perception of roughness with and without textured materials based on the two viewing modes. In the trial, the observer is required to carefully observe the change process of material properties until the perceptual standard is reached, which is regarded as the perceptual difference threshold (JND). In other words, JND is the minimum change threshold that an observer can observe from one material property value to the next threshold. Participants were asked to view specific material properties changes on the computer screen (2D) and HMD (VR) in this test.

According to the above description, each device automatically plays the change process of the roughness of the selected material at the speed of one frame per second. Using the within-subject design, participants were asked to observe the virtual environments from the starting point until they recognised the perceptible changes in material properties. The participants press the specified key to represent their perceived visual difference. The examiner recorded the number of times and values the participants found perceived differences. Figure 5.3 illustrates the entire test flow. MoA may be affected by habituation and expectation, resulting in experimental error.

Therefore, in the presentation of each group of stimuli, this study used to carry out alternately. The value of the first round changes from 0 to 1, and the second round is the opposite. However, due to the expected impact noise in the audience response and the parameter adjustment required to estimate the threshold accurately, the threshold task requires many repeated experiments to ensure the data's reliability. Therefore, each participant conducted 20 trials for each material under the two viewing devices, a total of 200 tests (5 materials, 2 devices, 20 tests).

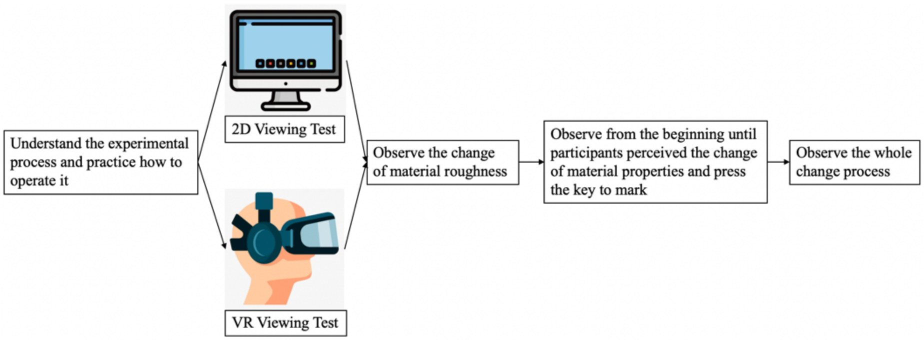


*Figure 5.3. The test process of the Method of Adjustment for testing the perceptual scale.*

## Section 5.3 Results

This study compares the participants' recognition of the roughness of five materials under two viewing modes. Therefore, the trial setting needs to determine how participants adjust the given stimulus to be reliably detected. Since the trial was repeated several times, the difference between the correct stimulus level and participants' response was recorded. The average value was taken as the measurement standard of material perception in all test groups. Each time participants can perceive the change of material properties corresponding to a specific JND value. The backstage recorded the number of times the user pressed the key, that is, the number of times all JNDs were perceived. Therefore, the perceived JND value (i.e., the roughness value of the material) under the corresponding times according to the roughness change process. The final JND constituted the perceptual scale of the material roughness. The research then analysed the collected data with both descriptive and inferential statistical methods.

### Section 5.3.1 The Perceptual Scale of the Materials in VR and 2D Viewing Modes

Psychophysics allowed researchers to create descriptive and predictive models through the probabilistic model of indirect measurements and reactions (Elliott, 2021). After a large number of repeatability trials, the test first established the perceptual scale of roughness for the five materials to reflect the participants' feelings. For each material, the data of 60 tests from 3 participants were obtained in both viewing modes. In order to better collect and count the obtained data, the study summarised all the data but ignored those values that the user perceived the roughness change less than 20% during the trials. This study then averaged the 60 sets of in-process JND values to obtain the final results. In this case, within the range of the roughness parameters, the participant could clearly perceive the appearances change on the related materials to generate the corresponding JND, which are sorted and drawn into the stimulus-response curves. Figure 5.4 shows JND perceptual curves for the five materials' roughness characteristics.

According to the statistical mean data, Figure 5.4 shows that the JND values of the five materials are different in VR and traditional 2D viewing modes. Each point on the fitted curve reflects a distinguishable stimulus intensity and accurately reflects the mapping to causal conditions. In Figure 5.4, the JND values are marked on the horizontal axis, whereas the vertical axis represents the perceived changes. The drawn curves can be plotted to show the trends of the perceived appearance changes against the change of roughness parameters. The perceptual changes in the stimulus (JND) and the standard stimulus are reflected in a logarithmic relationship. This also means that the scale of experimental measurements conforms to Weber's Law (Fechner *et al*. 1966), which determines the relationship between perceived changes in a stimulus and the actual changes. This law has been used to simulate how humans perceive certain features in visualisation and point out that the change in a stimulus that just noticeable is a constant ratio of the original stimulus (Quadri & Rosen, 2021).

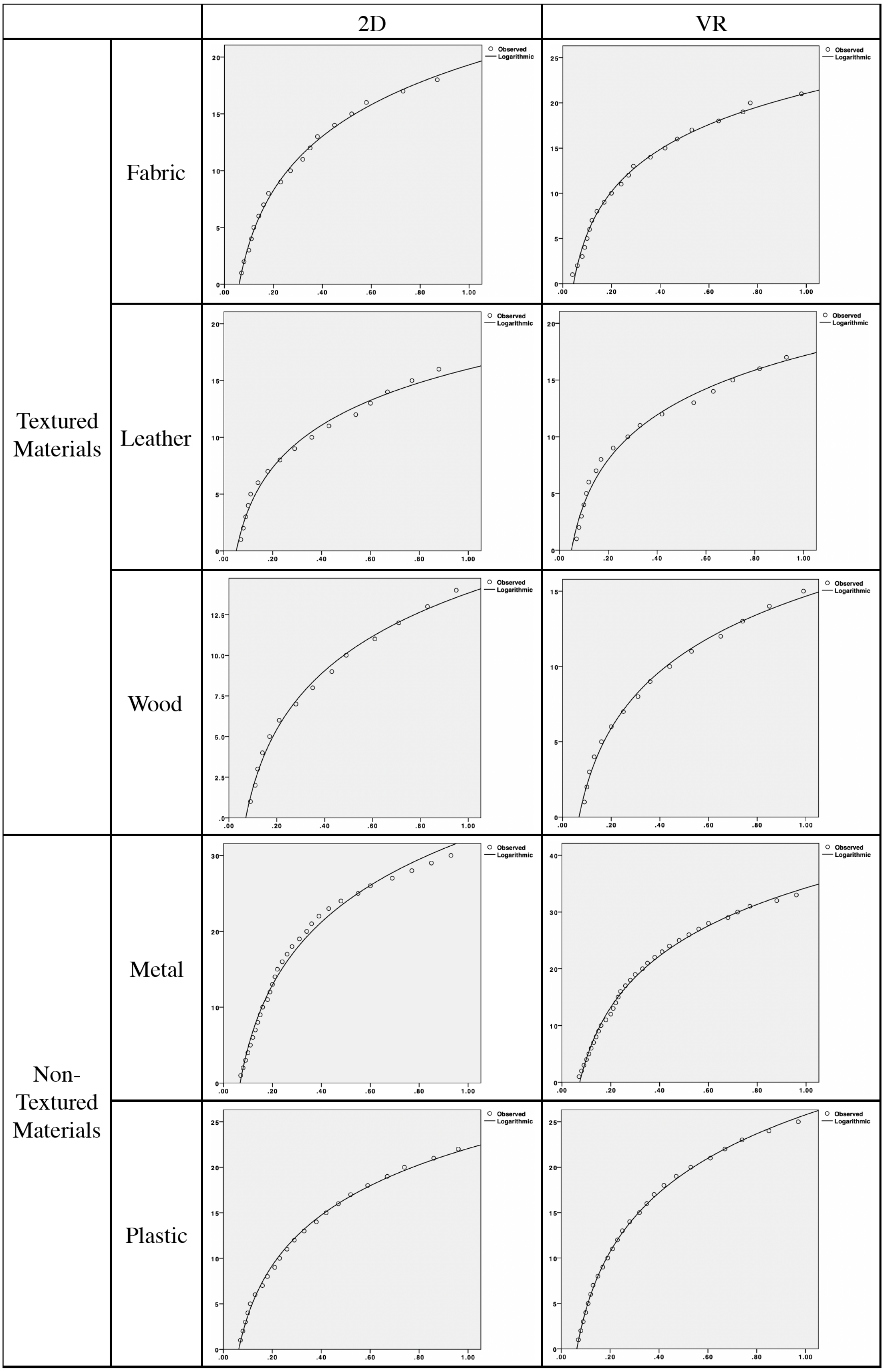


*Figure 5.4. The Mean Test Result of the Textured and Non-Textured Materials.*

## Section 5.3.2 Contrast of Roughness Perception Details in VR and 2D Viewing Modes

To better reflect the performance of participants in judging material roughness in VR and traditional 2D viewing modes, as well as the difference between textured and non-textured materials, this study statistically analysed the test results from three aspects: the starting position and ending position of perceived changes from each material and the number of JNDs. The starting point (the first JND) and ending point (the last JND) of the roughness change perceived by the participants represent the perceptible range of the roughness change or the effective perceptual interval. The number of JNDs directly reflects the perceived sensitivity of participants in the test process. Factor Analysis of Variance (F-ANOVA) is used to determine whether the individual and interaction of each factor are statistically significant (Collins *et al*. 2014) in the material perception. If the statistical p value is less than 0.05, the factors are significantly causing differences in the participants' performances on the material matching task.

### *Analysis of the First JND*

A one-way between-subjects ANOVA was conducted on materials and viewing modes as the independent variable, and the first JND as the dependent variable. The analysis results are shown in Table 5.3. Viewing modes (VR and 2D) [$F(1, 590) = 107.935$, $p < .001$] and the selected materials [$F(4, 590) = 239.571$, $p < .001$] were statistically significant factors affecting participants' judgment. The main effects of the two viewing modes corresponding to the materials can be seen more clearly in Figure 5.5. The horizontal axis represents five reference materials, while the value corresponding to the first JND is marked on the vertical axis. The blue line represents the value under the 2D viewing mode, and the green line represents the value under the VR viewing mode. The figure shows that the participant's recognition of the reference material differs in the first JND under two viewing modes. Since the deviation value of the test results is the average value, the smaller the value is the more quickly the participants can recognise. The statistical mean is shown in Table 5.4. From the figure, the research found that the position of the blue line is above the green line, which means that compared with the observation under 2D viewing mode, the participants made an early recognition on the roughness change under VR viewing mode. However, for metals and plastics, the performance of VR (metal: n = 60, M = .0718, SD = .00390; plastic: n = 60, M = .0723, SD = .00454) and 2D (metal: n = 60, M = .0722, SD = .00415; plastic: n = 60, M = .0728, SD = .00427) is very close, approaching the same result. The material with the most significant gap between VR (n = 60, M = .0738, SD = .00490) and 2D (n = 60, M = .0857, SD = .00533) is wood. The roughness perception value of wood in 2D viewing mode is the largest. On the other hand, whether under VR (n = 60, M = .0610, SD = .00543) or 2D viewing mode (n = 60, M = .0657, SD = .00563), the fabric is the material with the fastest perception of roughness change.

*Table 5.3. The results of the F-ANOVA tests on the first JND perception.*

| Source | df | F | *P* value |
|---|---|---|---|
| Viewing Mode | 1 | 107.935 | <.001* |
| Materials | 4 | 239.571 | <.001* |
| Error | 590 | | |

*Significant difference at α 99= .05

*Table 5.4. Descriptive statistics of the first JND perception.*

| | | | Range | Min. | Max. | Mean | SD | n |
|---|---|---|---|---|---|---|---|---|
| Textured Materials | Fabric | 2D | .02 | .05 | .07 | .0610 | .00543 | 60 |
| | | VR | .02 | .06 | .08 | .0657 | .00563 | 60 |
| | Leather | 2D | .01 | .06 | .07 | .0657 | .00500 | 60 |
| | | VR | .01 | .06 | .07 | .0627 | .00446 | 60 |
| | Wood | 2D | .02 | .08 | .10 | .0857 | .00533 | 60 |
| | | VR | .01 | .07 | .08 | .0738 | .00490 | 60 |
| Non-textured Materials | Metal | 2D | .01 | .07 | .08 | .0722 | .00415 | 60 |
| | | VR | .01 | .07 | .08 | .0718 | .00390 | 60 |
| | Wood | 2D | .01 | .07 | .08 | .0728 | .00454 | 60 |
| | | VR | .01 | .07 | .08 | .0723 | .00427 | 60 |

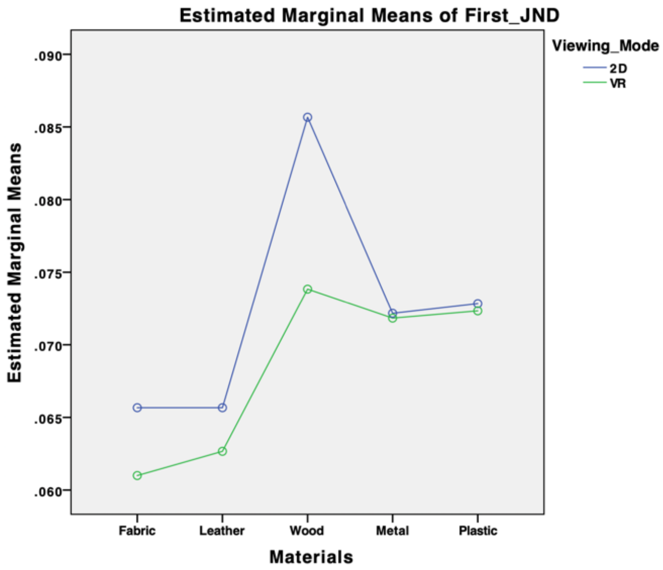


*Figure 5.5. Mean results of the first JND perception based on the five selected materials.*

### *Analysis of the Last JND*

Concerning the last perceived JND as the dependent variable, the trend is noticeably opposite to the first JND. As shown in Figure 5.6, the position of the blue line (2D) and the green line (VR) are switched. The mean values of the last JND are described in Table 5.5. This is interpreted as the time at which VR stops sensing the change of material roughness is later than the time at which 2D ends. However, the analysis results of the last JND are shown in Table 5.6. The display equipment [$F(1, 590) = 1.068$, $p = .302$] had no effect on the perception results for the last stage of roughness change. The study discussed this in the next section.

*Table 5.5. Descriptive statistics of the last JND perception.*

| | | | Range | Min. | Max. | Mean | SD | n |
|---|---|---|---|---|---|---|---|---|
| Textured Materials | Fabric | 2D | .10 | .87 | .97 | .9277 | .03072 | 60 |
| | | VR | .14 | .83 | .97 | .9312 | .02986 | 60 |
| | Leather | 2D | .09 | .88 | .97 | .9268 | .02671 | 60 |
| | | VR | .09 | .88 | .97 | .9302 | .01996 | 60 |
| | Wood | 2D | .10 | .86 | .96 | .9203 | .02822 | 60 |
| | | VR | .11 | .86 | .97 | .9323 | .02949 | 60 |
| Non-textured Materials | Metal | 2D | .11 | .86 | .97 | .9288 | .02935 | 60 |
| | | VR | .10 | .87 | .97 | .9292 | .03201 | 60 |
| | Wood | 2D | .11 | .87 | .98 | .9368 | .02740 | 60 |
| | | VR | .09 | .88 | .97 | .9387 | .02487 | 60 |

*Table 5.6. The results of the F-ANOVA tests on the last JND perception.*

| Source | df | F | *P* value |
|---|---|---|---|
| Viewing Mode | 1 | 1.068 | .302* |
| Materials | 4 | 4.924 | .001* |
| Error | 590 | | |

*Significant difference at α 101= .05

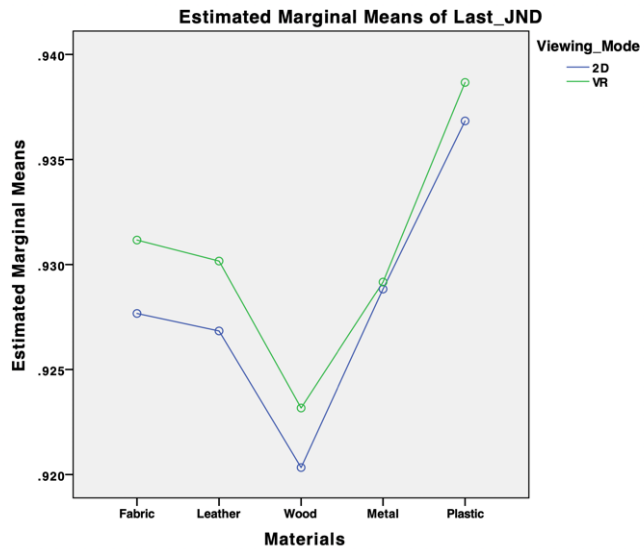


*Figure 5.6. Mean results of the last JND perception based on the five selected materials.*

*Analysis of the Number of JND*

As for the number of perceived roughness changes, viewing modes [F (1, 590) = 916.816, p < .001] help participants to make significantly responses to perceived roughness. The results are shown in Table 5.7. Participants evaluated the roughness changes of all materials according to different display devices. The average times are shown in Figure 5.7, and the corresponding data are shown in Table 5.8. Compared with other materials, the difference in the number of JND of metals under VR (n = 60, M = 31.90, SD = .681) and 2D tests (n = 60, M = 30.28, SD = .691) is huge. Interestingly, the identified position of the first JND of wood lags behind that of other materials. At the same time, the number of JNDs of the wood grain is the least. The test result VR (n = 60, M = 15.57, SD = .500) is one more than 2D (n = 60, M = 14.60, SD = .694). In terms of statistical results, except for wood, the statistical results of VR are about two more perceived JNDs than 2D. This result indicates that participants' perceived sensitivity to material roughness is improved in terms of VR viewing modes.

*Table 5.7. The results of the F-ANOVA tests on the perceived JND number.*

| Source | df | F | *P* value |
|---|---|---|---|
| Viewing Mode | 1 | 916.816 | <.001* |
| Materials | 4 | 12712.981 | <.001* |
| Error | 590 | | |

*Significant difference at α 102= .05

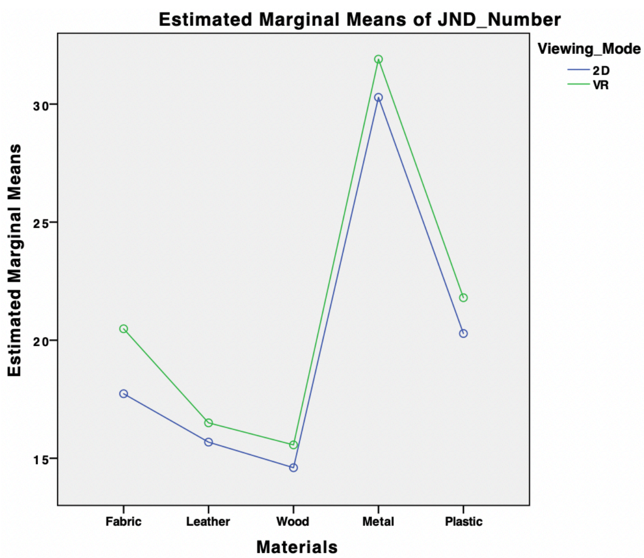


*Figure 5.7. Mean results of the perceived JND number based on the five selected materials.*

*Table 5.8. Descriptive statistics of the perceived JND number.*

| | | | Range | Min. | Max. | Mean | SD | n |
|---|---|---|---|---|---|---|---|---|
| Textured Materials | Fabric | 2D | 2 | 17 | 19 | 17.73 | .516 | 60 |
| | | VR | 2 | 19 | 21 | 20.48 | .567 | 60 |
| | Leather | 2D | 2 | 15 | 17 | 15.68 | .504 | 60 |
| | | VR | 1 | 16 | 17 | 16.50 | .504 | 60 |
| | Wood | 2D | 2 | 14 | 16 | 14.60 | .694 | 60 |
| | | VR | 1 | 15 | 16 | 15.57 | .500 | 60 |
| Non-textured Materials | Metal | 2D | 2 | 29 | 31 | 30.28 | .691 | 60 |
| | | VR | 2 | 31 | 33 | 31.90 | .681 | 60 |
| | Wood | 2D | 2 | 19 | 21 | 20.28 | .691 | 60 |
| | | VR | 2 | 21 | 23 | 21.80 | .777 | 60 |

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## Section 5.4 Discussion

In this chapter, the perceptual differences of surface material roughness and texture attributes between immersive VR viewing mode and traditional 2D viewing mode are studied by psychophysical methods. The study selected five materials (metal, plastic, fabric, leather, and wood) commonly used in product design research, which are divided into textured materials and non-textured materials to explore the influence of texture in material perception. The study applied a continuous roughness change effect to each material. The task performance of participants in immersive VR viewing mode and 2D viewing mode was compared, and the perceptual scale of each material was established by the psychophysical method. The results show that in the VR viewing mode, participants can recognise more roughness changes, and the texture attributes affect the participants' perception. These findings suggest that visual impressions in immersive VR viewing mode lead to different perceptual responses to rendered surface materials.

### Section 5.4.1 Perceptual Differences of JND in VR and 2D Viewing Modes

The current study investigated the five visual cues of material roughness to estimate the potential differences between the VR and traditional 2D viewing modes. There are some statistically significant relationships between material perception and the viewing modes, in which VR provides users with a more detailed roughness perception of the visual environment. The number of JNDs reveals the sensitivity of users' perception. As shown in Figure 5.8, after overlapping the fitting curves obtained by VR and 2D trials for each material, the research found that the differences in the number of JNDs are reflected in the middle region of stimulation intensity. Also, it can be seen from the statistical results that the difference between the two ends (JND at the starting and ending positions) is not obvious enough, especially for metal and plastic. Even at the beginning of stimulation, VR provided a slightly perceptiveness. According to the formula of Weber's law, the research found that the perceived change of stimulus intensity also increased gradually in the middle interval. Participants rely on the visual information, such as the light spot of material illumination, to judge the changes of such material properties (Fleming, 2012). However, for the roughness test, when the spot edge gradually blurred to the interval where the spot disappears, the participants' recognition with uncertainty (Coren *et al.*, 2014). In this range, VR provided more JND perceptual judgment than 2D mode and alleviated the influence of material texture, which mean that in immersive stereo vision, the stimuli intensity of material roughness is more intuitive on visual perception. In addition, as for the statistical results of the final JND value, the results also related to the users' dependence on the reference (light spot). When the light spot tends to disappear, it is difficult for users to judge the change of roughness from the material appearance clearly. Therefore, the value of the last JND in the two viewing modes cannot find significant difference after the mean value because of the interval differences of each trial.

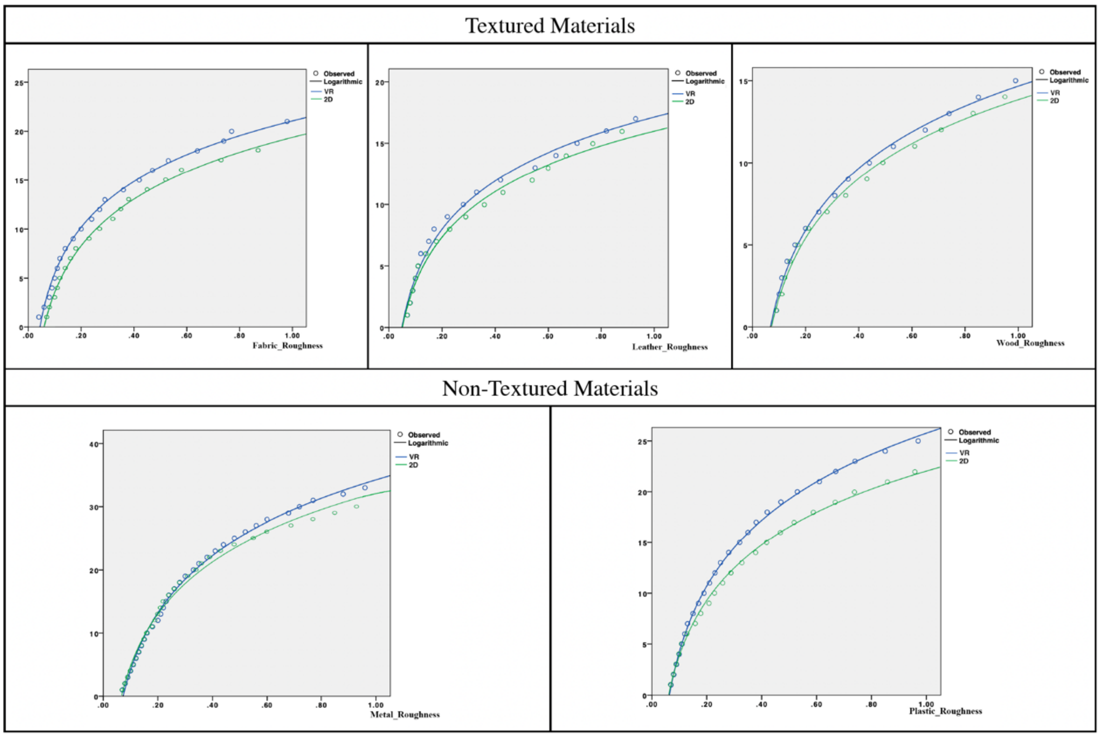


*Figure 5.8. Fitting curves for overlapping selected materials are based on VR and 2D tests.*

Previous studies have also discussed why VR can replace the traditional viewing mode for design evaluation because the traditional visualisation technology limits the experience to a piecemeal perspective (Bustillo *et al*., 2015). The results of these studies are reflected in the stereo perspective provided by VR rather than simulating reality (Tovares *et al*., 2014). The actual distinctions between inside and outside of VR are not being confused by users. When participants enter an immersive environment, emotions are triggered, and spontaneous cognitive behaviours are performed. However, this research explained the result according to Horiuchi *et al*. (2017). The amplitude range of visual stimulation in the central visual field through the 2D display mode is greater than that in the peripheral visual field. Gourishetti & Manivannan (2019) support similar results. The authors regarded the JND differences caused by the two devices as the visual environment provided by HMD and to eliminates visual noise. Because there is no other difference in the experimental settings of the two viewing modes except HMD. When people observe the surface of an object, they encode the information and stimulate perceptual judgment. Convergence is seen as the direction of the visual axis from each eye to the same target. Each eye perceives slightly different images of the same visual scene, and corresponds to the position of projection difference on the two retinas. The visual environment of VR uses the depth perception of binocular projection to enhance the stimulus intensity of users' recognition. The difference in the number of JNDs reflects the difference in the accuracy of monocular (2D) and binocular (VR) projection modes in distinguishing the stimulus intensity presented by materials. VR can provide users with a more centralized visual judgment environment.

### Section 5.4.2 The Number of JND on the Textured or Non-Textured Materials

Temporarily ignore the influence of visual perception difference caused by projection equipment, and then focus on the performance of textured and non-textured materials. In general, the performance differences of textured or non-textured materials in different viewing modes are obvious. This study noted that, no matter what viewing mode, the number of JNDs of non-textured materials is significantly higher than that of textured materials. Which indicated that the textural effect has visual interference in judging the result of roughness change.

For metals and plastics without textural attributes, participants' perception of metal roughness is more positive and engaged, even though the keen observation of plastic roughness ranked second among all material performance. Without the influence of texture mapping, this study considered that the difference between metal and plastic statistical results is related to the reflective characteristics. In the process of metal editing, this study set the metallic as the maximum value. Therefore, in addition to the influence of its roughness, the reflective characteristics of metal are more obvious visually. In other words, the visual judgment of roughness is based on the optical characteristics of material lighting, and a more conspicuous reflection effect is more favourable for users' judgment.

Compared with tactile perception, vision provides more appropriate ways to identify texture boundaries (Whitaker *et al.*, 2008). Visual coding processes the information that enables us to recognize and judge the object. Meanwhile, texture information is an inherent feature of the object's surface. Murgia & Sharkey (2009) proved that rich textured surfaces in virtual environments reduce the estimation of depth perception (Lawson *et al.*, 2015). The depth information of concave-convex becomes the additional information for visual judgment. In the texture materials category, the wood grain's roughness perception was not prominent compared with fabric and leather. This study speculated that it depends on the texture direction of the synthesized material, and summarised the texture directions of fabric, leather, and wood grain into diagonal, irregular, and horizontal directions. When participants observed objects, the object was placed in the centre of the sight, and the intersection of sight and texture direction guided the surface materials perception. Because the line of participants' sight is almost coplanar with the texture plane, it lacks information (Ware & Sweet, 2004). Previous studies have also found that humans can effectively use shadow information to perceive the shape of reconstructed surface materials (Koenderink & Van Doorn, 1995). This study interprets this result as the plane texture is parallel to the direction of the line of sight, which is not conducive to visual conflict. In addition, according to the comparison results of non-textured and textured materials, the research determined the negative impact of texture mapping on roughness judgment. Compared with leather, the number of JND in fabric tests increased slightly, which is inferred by the texture surface composition. The roughness of visual perception depends on the size and spacing of the elements constituting the textured surface (Ho *et al.*, 2006). On the contrary, the visual effect of twill spacing of fabric is small and compact, but the irregular grain spacing of leather is precise. In terms of test results, small spacing alleviated the negative effects of participants' visual judgment of roughness changes.

Finally, it is worth emphasizing some limitations of this study. The material selection of research is based on the representative materials of current product design, which are familiar to users. However, the materials category is not detailed enough. Therefore, it is challenging to unify the size and direction of each texture at the physical level and can clearly express the material effect. In addition, this study compared the users' judgment of roughness in a single lighting mode. In order to make the results more convincing, the impact of different light directions on material perception should be considered in subsequent research.

## Section 5.5 Summary

Material perception is a crucial factor in the design evaluation process, especially for user-centred product design. Understanding how material performance interacts with user-perceived effects is crucial to achieving accurate evaluation and saving development costs. As an emerging technology, VR is explored and applied in the design and development process. The strong "sense of presence" experienced by users in VR is supported to be effective for design evaluation. As more and more research focused on users' experience of design effect in the virtual environment, the research question proposed in this chapter become more relevant. The relationship between material visualisation and an immersive virtual environment is expected to provide a more practical method to understand the complex data, including highlighting the human connection to the data. This chapter studied how immersive VR and traditional 2D viewing experiences affect our perception of material roughness and discussed the impact of texture attributes on the perceptual effect. Taking the roughness of five materials (metal, plastic, fabric, leather, and wood) commonly used in product design as an example, this study adopted a psychophysical method to test, which integrates the user-perceived effect and the physical data of material properties. Using a real-time rendering engine, this study conducted a series of trials under VR and 2D viewing modes. The results revealed several significant insights. In short, in VR, the participants are more sensitive to visually detecting the change in material properties. Specifically, when comparing the recognition of material properties, more JNDs are found in the VR viewing mode. As for the influence of texture attributes, the significant difference is found in the identified JNDs with and without textured materials. The texture mapping also affects the participants' judgment of the changes in roughness.

These findings add a new dimension to VR and material visualisation research, that is, the perceptual difference in material properties. VR viewing mode provide more perceptibility of material property changes than the traditional mode. VR reveals more material details to facilitate design evaluation. In addition, texture mapping, as a standard simulated characteristic of materials, do hinder a users’ visual judgment in VR and traditional 2D viewing modes. These results give us and the relevant researchers deeper insights into presenting product materials in a virtual, immersive viewing environment.

Based on this, this study answered the differences in the perception of material properties between VR and traditional 2D viewing modes, which are reflected in the more detailed judgement and identification of material properties. Next, the thesis returns the research focus to the design evaluation activities, focusing on the different comparison of VR equipment at the emotional responses of material perception.

# Chapter 6 Difference of Material Perception at Perceptual Level in VR and 2D Viewing Modes

## Section 6.1 Introduction

Design evaluation is not only the perception of material physical properties, and material appearance often reflects the emotional signal of the product. Therefore, in this chapter, the research focuses on the perceptual comparison of visual materials at the emotional level. When the design standards are based on user satisfaction, designers consider the consumers' experience, the products' objective factors, and the consumers' subjective feelings. In other words, to achieve users' satisfaction, designers should map the users' emotions to the product based on the product's effectiveness. The design form should consider the functional and sustainable aspects of products as well as aesthetic and emotional significance to play a leading role in consumer preferences (Luchs *et al*., 2012). Acknowledged product design is usually close matching between designer and user perception. Consumers' emotions are caused by design variables of different dimensions in the whole product. Therefore, in the era of the experience economy, the quality of emotional product design determines consumers' purchase decisions (Guo *et al*., 2014). Zabotto *et al*. (2019) pointed out that one of the challenges designers face is how to express feelings to users when helping them analyse product design ideas. Therefore, once the users' subjective cognition is combined with reasonable data analysis, the scientific accuracy of the research can be improved (Fu *et al*., 2020). People's perception of products is often strongly affected by visual information.

In addition, the perception of materials can also induce users' emotional tendencies towards products. The visual information depends on the cognitive integration caused by relevant attributes such as light, colour, and material (Kataoka, 2018). Previous studies have repeatedly proved that the visual information of material appearance can help people quickly identify materials (Sharan *et al*., 2009, 2014; Fleming *et al*., 2013; Fleming, 2014; Ingvarsdóttir *et al*., 2020). Material perception is regarded as a reliable source of product appearance information and attached to the emotional dimension's meaning. The perceived materials enhance users' emotional feelings (such as temperature comfort) in addition to helping users judge specific product information (such as material type, colour, soft, or hardness). Zuo *et al*. (2016) showed that material information and texture patterns have a strong visual impact, helping users perceive "material expression" and convey the visual aesthetics of specific materials. Based on this, an in-depth understanding of how humans perceive material information plays a more critical role in selecting and combining materials in product manufacturing. The characteristics can improve the overall perceived value of the product. Of course, this means that the perceived characteristics of materials should be correctly communicated to consumers.

From the perspective of human experience, VR is defined as a "real or simulated environment" (Radianti *et al*., 2020). In the VR system, the immersion makes the perceiver experience the sense of presence, more like exploring the perceiver's physical existence in the virtual environment (Valencia-Romero & Lugo, 2017). de Gelder *et al*. (2018) believe that the cognitive theory of VR experience is the key to exploring VR's usefulness as a research tool, especially in emotional research. Earlier studies based on the 2D viewing mode, that is, the mode of projecting the 3D model on the 2D plane to support the research of product aesthetics (MacDonald *et al*., 2009; Orsborn *et al*., 2009; Kelly *et al*., 2011; Lugo *et al*., 2015, 2016; Valencia-Romero & Lugo, 2017). However, the depth perception and visual cues provided by the VR viewing mode can better comprehend the subject's perception (Pizlo, 2010; Higgins, 2012). For designers and producers, the traditional 2D or VR viewing mode to present design effects is to pay more attention to consumers' emotional needs for product appearance. Design evaluation should involve the product's visual attractiveness and the potential of the product quality and appearance. Therefore, the combination of product characteristics and consumers' needs has become the standard of excellent product design. It is relatively one-sided to use the designer's perceptual thinking and creativity for design or overemphasise the involvement of quantitative data research in emotional cognition (Xiao & Cheng, 2020). VR technology is widely used in collaborative design (Koutsabasis *et al*., 2012), user experience evaluation (Rebelo *et al*., 2012), and other fields because VR is user-centred research. Although the development principle of VR is to generate convincing virtual scenes, there is still debate on whether visual perception improves the VR experience (Rizzo & Koenig, 2017; Pan & Hamilton, 2018; Slater *et al*., 2020; Vasser & Aru, 2020).

Although some psychological and computer disciplines can explore people's perception of materials in design field, the information on product design specifications still needs to be easy and convenient to understand for designers (Karana *et al*., 2008). The theory of embodied cognition holds that one of the perception meanings is to obtain a large amount of information only through observation without physical interaction and use this information to guide the planning of future actions (Bridgeman & Tseng, 2011). According to Groth (2017), when designers explore the concrete mode in describing the materials, they achieve the production experience in real life. Early embodied cognitive theory pointed out that people's interaction with tools reshaped the way people think and perceive, and this kind of thinking is realised through the body, not just determined by the brain (Kirsh, 2013). The VR viewing mode can help users feel a sense of embodied feeling (Hofer *et al*., 2017) to improve the user experience (McMahan *et al*., 2016, Shin & Biocca, 2017). Although authenticity is still the research focus of VR applications, it should be discussed more widely regarding users' feelings of visual expression of materials in VR.

### *Research Approach*

The research method of this chapter is based on Kansei Engineering (KE). The application fields of KE include automobile, machinery, food industry, household building materials, electrical appliances, and the garment and cosmetics industry (Lee *et al*., 2021). Kansei, a Japanese word, refers to the intuitive psychological behaviour of human beings who feel a particular impression from external stimuli (Nagamachi, 2017). KE has proved to be a comprehensive method for evaluating product characteristics. The concept of KE (Nagamachi, 1995) originated in Japan in the 1990s, which aims to analyse data related to human emotions and generate measurable design specifications through the association between words and product attributes (Vieira *et al*., 2017).

### *Structure of the Chapter*

Since users' perception results are usually implicit (Fu *et al*., 2020), this research help designers identify and analyse users' emotional needs to meet their expected design effects. Whether the experimental results based on the traditional evaluation method (2D viewing mode) can be extended to the immersive VR viewing mode is still a problem to be studied. In this chapter, the research answers the following question:

*"How is the visual difference between VR and 2D reflected in the perceptual expression of materials?"*

Therefore, based on the KE approach, this study explains the difference between the users' emotional responses generated by the material perception in the VR and traditional 2D viewing modes. The two viewing modes when viewing the same scene are shown in Figure 4.1. In other words, when the users are in an environment surrounded by materials, the perceptual differences of users are based on the embodied experiences (immersive VR viewing mode) and unembodied experiences (traditional 2D viewing mode). The experiment collected 6 perceptual criteria in semantic forms, including rigidity, formality, fineness, softness, modernity, and irregularity. In section 6.4, the results reveal insights into how material characteristics affect the users' emotional responses. And this study discussed how these findings provide a new dimension of emotional design experience for the subsequent development of predictive customer preference products in section 6.5.

## Section 6.2 User Study

This study explores the differences in users' emotional responses to materials perception in a closed space based on immersive VR and non-immersive 2D viewing modes. Users has triggered corresponding emotional responses through light, materials, and textures under the spatial experience (Naz, 2016). Therefore, this study determines the Kansei Words as the evaluation criteria, based on which users evaluate the perceived experience under the two viewing modes.

### Section 6.2.1 Theoretical Fundamental of Evaluation Scheme

KE extends at least eight methods (López *et al*., 2021), and its evaluation process and data form are slightly different. Among them, KE Type I is often used to identify meaningful design details of products (Nagamachi, 1995). Figure 6.1 shows the steps constituting the method. This study follows KE Type I program to evaluate users' emotional responses of material in space. This method requires identifying a group of relevant perceptual words that can describe the subjective feeling according to the test background. The choice of perceptual words is usually representative or authoritative. These words use the Likert scale to improve the accuracy of user scoring to collect data in the follow-up trial—a clearly defined classification based on the statistical results for subsequent testing of users.

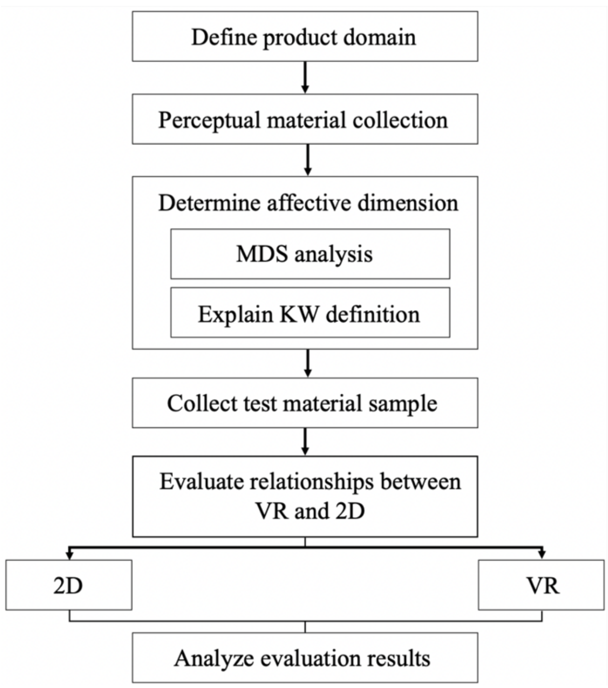


*Figure 6.1. KE Type I flowchart used in the research.*

### Section 6.2.2 Domain and Semantic Space

This study focused on users' Kansei perception of materials. The real-world experience is essentially multi-sensory and three-dimensional (Naz *et al*., 2017). When we observe the product's appearance, the product's material looks different from the perception when the product is in the usage environment, such as furniture, car interior, etc. Therefore, unlike previous studies on material perception using many material boards or material models, this study pays more attention to the users' experience and feelings of materials in the environment surrounded by materials. Therefore, the perceptual responses of materials in space are worthy of attention in this study.

#### *Collect Kansei Words in Closed Space*

KW can intuitively reflect the emotional needs of users (Guo *et al*., 2014). Collecting users' emotional feelings about material representation and effectively identifying KW play a decisive role in KE research.

*Table 6.1. Collected emotional Kansei words.*

| No. | Kansei Word | No. | Kansei Word | No. | Kansei Word |
|---|---|---|---|---|---|
| 1 | Luxury | 11 | Cool | 21 | Romantic |
| 2 | Pleasant | 12 | Clean | 22 | Science |
| 3 | Harmonize | 13 | Quiet | 23 | Repressive |
| 4 | Calm | 14 | Ola Mannish | 24 | Gentle |
| 5 | Narrow | 15 | Delicacy | 25 | Cheap |
| 6 | Simple | 16 | Vivacious | 26 | Classic |
| 7 | Practical | 17 | Business | 27 | Chic |
| 8 | Elegant | 18 | Hard | 28 | Avant-garde |
| 9 | Spacious | 19 | Ordinary | 29 | Exaggerate |
| 10 | Crowd | 20 | Warm | 30 | Dynamic |

Therefore, the scope of word collection should be screened from the perceptual adjectives facing consumers to ensure that consumers can identify and understand the selected adjectives well. Otherwise, it may affect the accuracy of emotional design results. Before the test, this study collected all the perceptual adjectives in six magazines on automotive interior design, interior design, and space design in the past two years, namely Car and Driver, Top Gear, Frame, and ID. Interior, Home Style, and Domus. A total of 116 perceptual adjectives (single words, ignoring descriptive sentences) were collected, and 30 adjectives with the highest scores were finally selected according to the repetition rate. The selection results are shown in Table 6.1.

### *Multi-Dimensional Scaling*

The effectiveness of Kansei evaluation depends on the rationality of extracting perceptual classification from the collected KW, which is used to comprehensively evaluate users' perceptual judgment. As a computing technology that can be used to visualise data information (Machado *et al*., 2021), MDS is used to detect potential dimensions and visually present the similarity between items to improve recognition efficiency (Li *et al*., 2017). Jia & Tung (2021) stated that MDS limits the perceptual dimension to some stimuli and derives reliable results. This study used SPSS MDS analysis (PROXSCAL) to screen representative KW. MDS is more objective than the previous manual classification methods in providing participants with the definition of evaluation semantics.

This study designed an online questionnaire to judge the similarity between the 30 perceptual words extracted before. 30 perceptual words listed in the questionnaire are presented in matrix form. 200 volunteers participated in the questionnaire survey (n = 200, M = 33.78, SD = 12.46). This study published the questionnaire on the public online platform, and these participants were randomly recruited through the network. They were asked to rate the similarity of every two words in the matrix from 0 (completely different) to 10 (completely similar). In addition, the order of words in the questionnaire is random to avoid the potential adaptation effect.

*Table 6.2. Stress and Fit Measures.*

| | |
|---|---|
| Normalised Raw Stress | .07941 |
| Stress-I | 2.8180[a] |
| Dispersion Accounted For (D.A.F) | .92059 |
| Tucker's Coefficient of Congruence | .95947 |

PROXSCAL minimizes Normalized Raw Stress.

a. Optimal scaling factor = 1.086.

This study used Kruskal (1964)'s statistical stress criteria. That is, lower stress measurements (minimum 0) and higher fitting measurements (maximum 1) to show that the solution is suitable. The stress and fit measures in this study are shown in Table 6.2. The Normalised Raw Stress here is 0.07941, which is approaching 0. The statistical value of D.A.F is 0.92059, which is approaching 1. View of the model can be explanatory, and meet Kruskal's criteria. SPSS processed the data results collected by the questionnaire, and the analysis diagram of MDS is shown in Figure 6.2.

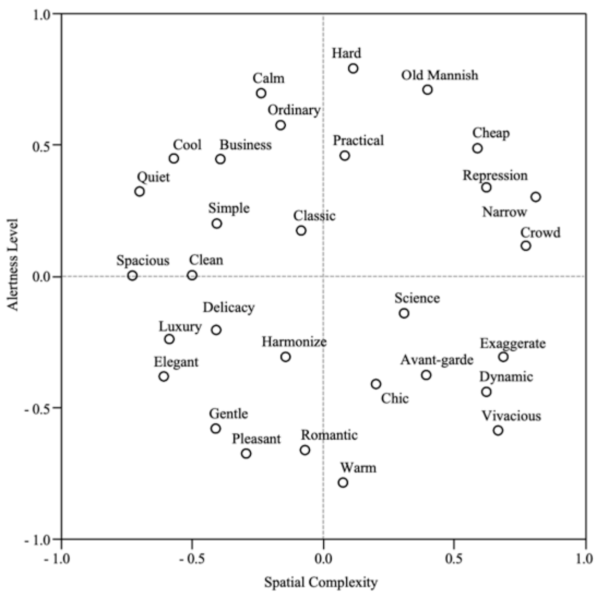


*Figure 6.2. Overall MDS solution, based on average similarity judgments of N = 200 participants.*

According to the results generated by MDS, the researchers obtained the following explanations for cluster analysis:

One end of Dimension 1 is spacious, quiet, and clean, focusing on the space's quiet and refined. The other end is crowded, narrow, and exaggerated, focusing on the complexity and randomness of a space. Therefore, this research marks this dimension as "Spatial Complexity," a combination of simple complex and static dynamics.

For the other dimension, the end of the higher score is hard, calm, and old mannish, reflecting a state of indifference. The lower end of the score reflects an easy-going and cheerful mood because it is warm, romantic, and vivacious. Dimension 2 is labelled "Alertness Level," which explains the feeling of personal characteristics guided by personality and emotion.

The researchers grouped 30 words through visual examination, as shown in Figure 6.3. Six perceptual criteria required for the subsequent research are formed: Rigidity, Formality, Fineness, Softness, Modernity, and Irregularity. The interpretation of the updated six KW after grouping is shown in Table 6.3.

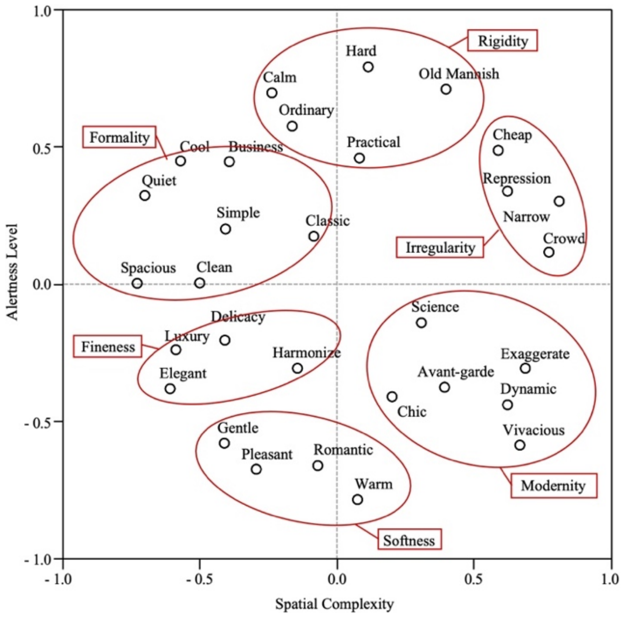


*Figure 6.3. Overall MDS solution with indicated clusters and labels.*

*Table 6.3. Kansei Key Words Description.*

| No. | Kansei words | Sub-words | Description |
|---|---|---|---|
| 1 | Rigidity | Hard<br>Calm<br>Ordinary<br>Practical<br>Old Mannish | The words in this group are developing towards a more practical and restrained meaning, which includes old mannish and calm. It is called "Rigidity" because the overall feeling is about sticking to themselves and will not be flexible easily. |
| 2 | Formality | Cool<br>Quiet<br>Business<br>Simple<br>Classic<br>Spacious<br>Clean | The second group of clusters contains a sense of business, cold and classical atmosphere, and the word "Formality" is well described. |
| 3 | Fineness | Delicacy<br>Luxury<br>Elegant<br>Harmonize | The third group directly chooses to use "Fineness" as the representative. Whether it is luxury or elegant, it seems to express the meaning of delicacy directly. |
| 4 | Softness | Gentle<br>Pleasant<br>Romantic<br>Warm | Gentle, warm, pleasant, and romantic, all these four words reveal a feeling of being wrapped gently, so they are marked as "Softness". |

| | | | |
|---|---|---|---|
| 5 | Modernity | Science<br>Avant-garde<br>Chic<br>Vivacious<br>Dynamic<br>Exaggerate | This group seems dissimilar, but whether it is science, avant-garde, and dynamic, it seems to be various distinctive descriptions extended with the development of modern society. Being called "Modernity" also represents a more open and diverse feeling. |
| 6 | Irregularity | Cheap<br>Repressive<br>Narrow<br>Crowd | The sixth group, repression, narrow, and crowd, are combined with the feeling of cheapness, all of which show a disordered space, so "Irregularity" is selected as the representative. |

### Section 6.2.3 Apparatus and Display

• Devices Details: In terms of equipment selection, this study used HTC Vive Pro to provide a VR viewing experience, non-immersive traditional 2D viewing mode and present it with a calibrated 17-inch, 4.5Ghz game notebook Alienware AREA-51M.

• Visual Distance and Size: Although the maximum resolution provided by the two devices is different, this study has pre-set the same visual resolution in UE4 before the test, that is, 1920x1080pixels. And the visual distance is 2m.

• Display Software: This study chose Unreal Engine 4 (UE4) to create the test environment and execute the test content. Visual content is projected on VR devices and desktop computers, respectively.

### Section 6.2.4 Stimuli

The research direction of this thesis is material perception. The materials used in the design evaluation are preliminarily screened in this study. Since most of the synthesised materials are simulated by a rendering engine, this study uses the material map in Adobe online database (https://substance3d.adobe.com/assets). This kind of online database gathers the renderings of complete fitting materials and is often used by designers in the simulation activities of the various VP. This study does not consider the transparent and translucent materials because considering the complex optical properties that affect the materials' performance. Therefore, the database has seven types of opaque materials: fabric, leather, metal, paper, plastic, stone, and wood. These seven categories include most of the materials commonly used in daily design. According to the downloads statistics, this study selects five materials in each material category, so there are 35 kinds of test materials (7x5). To avoid the effect of material colour on perceptual evaluation as much as possible, this study mostly chose neutral colour (black, white, and grey) materials in the selection process. At the same time, to not cause cognitive impairment to users, this study reserved materials with specific colours, such as wood and denim. The visual effects of materials are shown in Figure 6.4.


*Figure 6.4. Collected materials (7 categories and 5 material per category).*

## Section 6.2.5 Participants

Forty people (n = 40, 16 females, 24 males) within the age range 19–36 (M = 24, SD = 3.89), were recruited as volunteers to participate in the evaluation tests. All participants were randomly recruited from the Xi'an Jiaotong-Liverpool University, and there was no restriction on the background or major of the participants. All tests were carried out in the laboratory provided by the institution. Since long-term use of HMD devices may cause dizziness (Desai *et al*., 2014), it is often necessary to appropriately extend the trial of each participant, and the research provides participants with sufficient rest time during the trial. The ethics committee approved the study of the XJTLU’s institution.

## Section 6.2.6 Procedure

According to Harvey (2018), a person's total living space should be at least $6m^2$ and at least 2.5m from the floor to the ceiling to avoid causing psychological depression. In this test, this study built a $16m^2$, 3m high rectangular hollow space in UE4. This room has no furniture except doors and windows. Figure 6.5 shows the scene diagram used as 2D viewing mode in the unchanged version. The default light source of UE4 is used for the construction and lighting of the model. The material drawing is attached to the wall in the room for testing. According to Vangorp (2007) and other studies, the shape of the test object often leads to the wrong judgment of material perception, and the object with irregular shape seems to be a better choice. Although this conclusion is still under discussion, in this study, this study placed an irregularly shaped object in the room (the stone shape in the default source of UE4, as shown in Figure 6.5). Although participants are not required to cast their eyes on the irregular object, the purpose of this placement is to avoid the cognitive burden caused by participants' obstacles to material recognition.

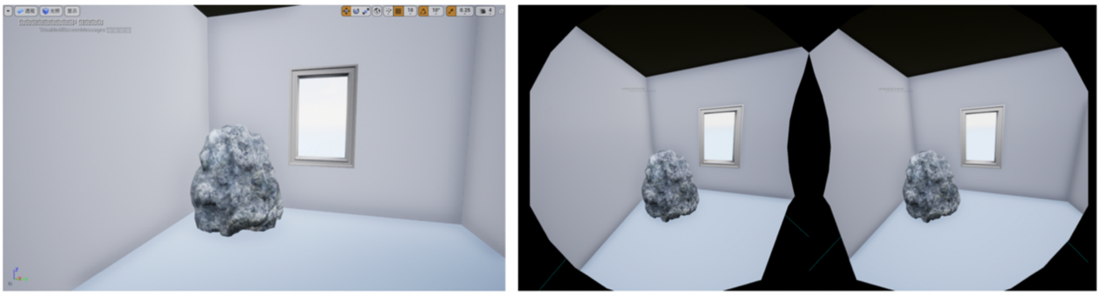


*Figure 6.5. The viewing scene under 2D viewing mode and VR viewing mode.*

In addition, since the participants sat on the chair during the whole trial process. To comply with the ergonomic principle, the viewing height in UE4 was set at 1.2m conforms to the eyes height when people are sitting (Abd Rahman *et al*., 2018). The participant's viewing position is placed in the middle of the room. The scene setting is shown in Figure 6.6.

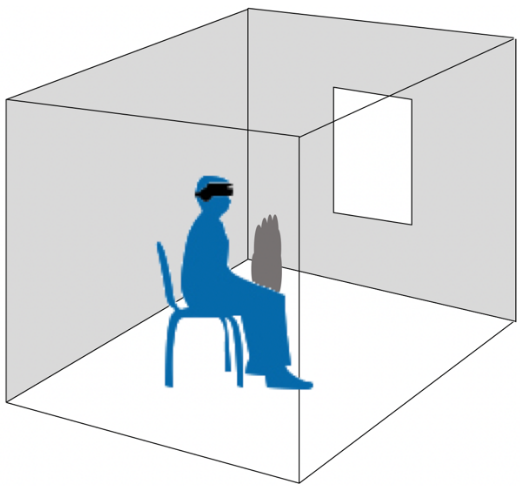

*Figure 6.6. Scene setting (figure shows the scene viewed by the user in VR viewing mode, and the scene in 2D viewing mode is the same).*

The walls and the irregular object of the room are all attached with the same material, and the scene settings of 2D mode and VR mode are the same. Participants have 360 degrees of freedom to observe in this environment, while their initial position in the test scene remains fixed. Under the VR viewing condition, participants wear HMD to observe the scene inside the room. The HMD acts as an output device, and the participants' visual rotation is connected with the physical rotation of the HMD. Instead of non-immersive 2D viewing modes, users look at the same room type on UE4 on the computer. In order to achieve similar interaction when using the screen, this study allows participants to drag the scene with the mouse to observe more clearly in the 2D viewing environment (like 360 panoramas). Therefore, in the VR viewing environment, the study did not have a fixed position of HMD, and participants can turn their heads freely to view the room. Participants rated six updated Kansei words according to the material in the room they saw. According to the principle of the Likert scale, the score range was selected from 0 (entirely inconsistent) to 7 (entirely consistent). After scoring a material, the experimenter will help the participants debug the following test scenario. There were 35 test materials in this trial, which means that participants rated the materials in 70 scenes (35x2) with two devices. It should be emphasised that both the display order of materials tested by each participant and the test order of equipment are random. After the participants evaluated all the materials under the two equipment tests, the researchers collected the evaluation scores and conducted an informal interview with each participant.

## Section 6.3 Results

The test results are presented in the form of numerical values. High values represent strongly perceive the material's corresponding emotional attributes. The collected data were analysed by factor analysis of variance (F-ANOVA) to determine whether the interaction between the material and the viewed device was statistically significant.

*Table 6.4. The F-ANOVA analysis results.*

| Measures | | df | F | Sig. |
|---|---|---|---|---|
| Device | Rigidity | 1 | 16.633 | <.001* |
| | Formality | 1 | 23.136 | <.001* |
| | Fineness | 1 | 62.757 | <.001* |
| | Softness | 1 | 27.634 | <.001* |
| | Modernity | 1 | 7.168 | .007* |
| | Irregularity | 1 | 2.039 | .153* |
| Material | Rigidity | 34 | 14.909 | <.001* |
| | Formality | 34 | 26.136 | <.001* |
| | Fineness | 34 | 13.740 | <.001* |
| | Softness | 34 | 21.249 | <.001* |
| | Modernity | 34 | 19.309 | <.001* |
| | Irregularity | 34 | 76.542 | <.001* |
| Device*Material | Rigidity | 34 | 2.819 | <.001* |
| | Formality | 34 | 2.100 | <.001* |
| | Fineness | 34 | 3.370 | <.001* |
| | Softness | 34 | 3.237 | <.001* |
| | Modernity | 34 | 3.757 | <.001* |
| | Irregularity | 34 | 4.383 | <.001* |
| Error | | 2730 | | |

*Significant difference at α 125= .05

A one-way between-subjects ANOVA was conducted on the emotional responses of users under the two displayed devices (VR and 2D viewing mode). Participants in each viewing mode were further evaluated six perceptual criteria, irregularity, formality, fineness, softness, modernity, and irregularity groups. The analysed results are shown in Table 6.4. The devices significantly affects the perception of rigidity [F (1, 2730) =

16.633, $p < .001$], formality [$F (1, 2730) = 23.136$, $p < .001$], fineness [$F (1, 2730) = 62.757$, $p < .001$], softness [$F (1, 2730) = 27.634$, $p < .001$], modernity [$F (1, 2730) = 7.168$, $p = .007$]. According to the materials performance, the emotional changes perceived by participants seem to be different due to the two viewing devices of VR and computer. However, no significant difference was found in the perceived impact of viewing devices on irregularity [$F (1, 2730) = 2.039$, $p = .153$]. The tested materials and perceptual dimensions have a significant impact in terms of emotional analysis. In addition, the interaction between viewing equipment and materials significantly affects each perceptual dimension's judgment. These statistical analysis results mean that participants will have different emotional responses according to the combination of equipment and material characteristics.

Figure 6.7 clearly shows the significant impact of experimental factors on perceptual judgment. According to the evaluated scores of participants, the yellow area represents that the users' perceptual score of related materials in 2D viewing mode is higher than that in VR viewing mode. The green area indicates that the evaluation score of VR mode is higher. The blue area indicates that the ratings of the two viewing modes are the same. The descriptive statistics are shown in Table 6.5. Also, the relevant information related to the corresponding materials is shown in Appendix 1.

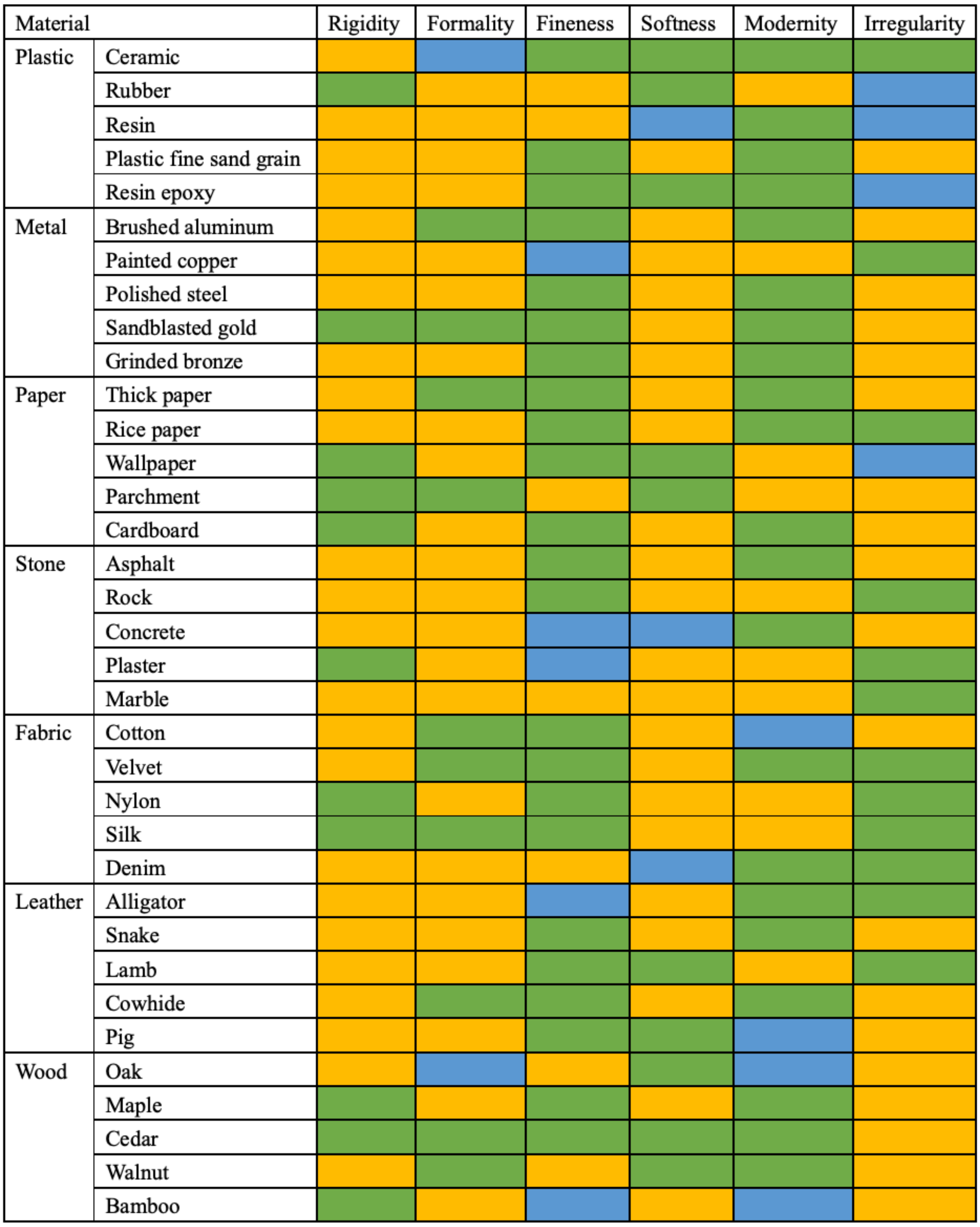


*Figure 6.7. The device impact of experimental factors on perceptual judgment.*

*Table 6.5. Descriptive statistic for users' emotional responses.*

| | Rigidity | | Formality | | Fineness | | Softness | | Modernity | | Irregularity | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2D Mean (SD) | VR Mean (SD) | 2D Mean (SD) | VR Mean (SD) | 2D Mean (SD) | VR Mean (SD) | 2D Mean (SD) | VR Mean (SD) | 2D Mean (SD) | VR Mean (SD) | 2D Mean (SD) | VR Mean (SD) | n |
| Plastic 1 | 3.70 (1.572) | 3.00 (1.109) | 3.80 (2.255) | 3.80 (.833) | 3.60 (1.582) | 3.70 (1.363) | 3.30 (1.436) | 3.60 (1.446) | 3.10 (1.392) | 3.20 (.608) | 2.50 (1.132) | 2.30 (1.114) | 40 |
| Plastic 2 | 3.20 (1.800) | 3.30 (1.698) | 3.90 (1.722) | 3.80 (.992) | 4.00 (1.502) | 3.80 (1.181) | 2.40 (1.297) | 2.70 (1.018) | 4.90 (1.598) | 4.60 (1.707) | 1.70 (.791) | 1.70 (1.018) | 40 |
| Plastic 3 | 3.40 (2.228) | 3.20 (1.620) | 4.30 (1.114) | 3.10 (1.236) | 3.60 (1.646) | 3.20 (1.488) | 3.00 (1.812) | 3.00 (1.359) | 4.20 (1.488) | 4.30 (1.572) | 1.80 (.883) | 1.80 (.883) | 40 |
| Plastic 4 | 4.60 (1.646) | 3.20 (1.620) | 4.60 (1.128) | 4.00 (1.695) | 3.20 (1.418) | 4.30 (.791) | 3.40 (1.297) | 3.00 (1.198) | 4.20 (1.091) | 5.20 (.992) | 1.40 (.810) | 1.30 (.464) | 40 |
| Plastic 5 | 4.80 (1.556) | 3.90 (1.392) | 4.80 (1.418) | 4.40 (1.297) | 2.40 (1.215) | 3.20 (.833) | 3.10 (1.722) | 3.40 (1.215) | 3.80 (1.181) | 4.60 (1.128) | 1.50 (.816) | 1.50 (.679) | 40 |
| Metal 1 | 5.40 (1.215) | 4.20 (1.620) | 4.30 (1.742) | 4.40 (1.128) | 2.20 (.992) | 4.30 (1.363) | 2.80 (1.682) | 2.70 (.791) | 3.00 (1.502) | 4.60 (1.646) | 2.90 (1. 945) | 2.30 (1.203) | 40 |
| Metal 2 | 3.60 (1.033) | 3.20 (1.265) | 3.20 (1.742) | 2.60 (1.297) | 3.50 (1.769) | 3.50 (1.450) | 4.80 (1.682) | 3.40 (1.297) | 3.80 (1.418) | 2.90 (1.533) | 1.80 (1.091) | 3.70 (1.924) | 40 |
| Metal 3 | 2.10 (1.464) | 1.70 (1.203) | 2.10 (1.661) | 1.40 (.928) | 2.20 (1.418) | 2.70 (1.203) | 2.00 (1.633) | 1.50 (.679) | 3.30 (1.870) | 3.50 (1.826) | 6.10 (1.533) | 5.70 (1.363) | 40 |
| Metal 4 | 3.00 (1.867) | 3.20 (1.911) | 2.70 (1.436) | 2.90 (2.048) | 4.10 (1.533) | 4.60 (1.582) | 3.00 (.641) | 1.90 (.841) | 4.30 (1.363) | 4.70 (1.636) | 2.70 (1.506) | 2.50 (1.769) | 40 |
| Metal 5 | 2.50 (1.585) | 2.10 (1.533) | 2.10 (1.150) | 1.60 (.810) | 2.30 (1.203) | 2.90 (1.464) | 2.10 (1.392) | 1.80 (.992) | 3.20 (1.418) | 3.60 (1.516) | 6.10 (.955) | 5.40 (1.878) | 40 |
| Paper 1 | 4.50 (1.519) | 3.50 (1.881) | 4.40 (1.707) | 4.80 (1.742) | 3.30 (1.698) | 4.20 (1.181) | 3.50 (1.219) | 3.40 (1.297) | 4.20 (1.488) | 4.90 (1.236) | 1.50 (.816) | 1.30 (.464) | 40 |
| Paper 2 | 3.30 (1.506) | 3.00 (1.812) | 2.80 (1.181) | 2.50 (1.038) | 2.90 (1.598) | 3.10 (1.533) | 2.10 (.841) | 2.00 (.784) | 4.20 (1.556) | 4.60 (1.215) | 4.00 (1.754) | 5.00 (1.281) | 40 |
| Paper 3 | 3.50 (1.132) | 3.80 (1.265) | 4.10 (1.057) | 3.80 (1.418) | 3.10 (1.057) | 3.40 (1.374) | 3.30 (1.285) | 3.40 (1.516) | 3.70 (1.285) | 3.50 (1.219) | 2.60 (1.297) | 2.60 (1.646) | 40 |

| | Rigidity | | Formality | | Fineness | | Softness | | Modernity | | Irregularity | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2D Mean (SD) | VR Mean (SD) | 2D Mean (SD) | VR Mean (SD) | 2D Mean (SD) | VR Mean (SD) | 2D Mean (SD) | VR Mean (SD) | 2D Mean (SD) | VR Mean (SD) | 2D Mean (SD) | VR Mean (SD) | n |
| Paper 4 | 2.80 (1.418) | 3.80 (1.911) | 2.10 (1.317) | 2.30 (1.203) | 2.70 (1.285) | 2.60 (1.374) | 2.50 (1.450) | 3.10 (.955) | 2.80 (1.344) | 2.10 (.545) | 4.80 (1.488) | 3.80 (1.556) | 40 |
| Paper 5 | 2.90 (1.392) | 3.20 (1.418) | 2.70 (1.572) | 2.40 (1.033) | 2.80 (1.344) | 3.10 (.709) | 4.20 (1.418) | 3.80 (1.265) | 3.00 (1.695) | 3.20 (1.265) | 2.90 (2.098) | 2.80 (1.742) | 40 |
| Stone 1 | 3.10 (1.392) | 2.00 (1.502) | 3.00 (1.359) | 1.70 (1.018) | 3.30 (1.506) | 3.80 (1.418) | 3.00 (1.569) | 2.20 (.883) | 3.70 (1. 436) | 4.30 (1.018) | 4.70 (1.5729) | 4.30 (1.363) | 40 |
| Stone 2 | 3.50 (2.038) | 3.40 (1.582) | 2.90 (1.533) | 2.50 (1.519) | 3.20 (1.344) | 3.50 (1.450) | 3.20 (1.800) | 2.30 (1.018) | 4.80 (.992) | 3.70 (1.572) | 3.50 (1.301) | 4.20 (1.091) | 40 |
| Stone 3 | 3.90 (2.048) | 3.40 (1.516) | 3.30 (1.636) | 3.20 (1.091) | 2.80 (1.620) | 2.80 (1.344) | 2.50 (1.769) | 2.50 (1.132) | 3.10 (1.057) | 4.30 (1.572) | 4.70 (1.870) | 4.20 (1.334) | 40 |
| Stone 4 | 4.00 (1.867) | 4.30 (1.870) | 3.40 (1.374) | 2.60 (.810) | 3.50 (1.132) | 3.50 (1.377) | 2.60 (1.297) | 2.30 (1.114) | 3.50 (1.132) | 3.40 (1.128) | 4.10 (1.661) | 4.50 (1.769) | 40 |
| Stone 5 | 2.90 (1.892) | 2.50 (1.301) | 3.00 (1.359) | 2.10 (1.150) | 3.80 (1.344) | 3.00 (1.359) | 3.60 (1.446) | 2.50 (1.132) | 4.10 (1.722) | 3.50 (1.301) | 4.10 (1.464) | 5.00 (1.432) | 40 |
| Fabric 1 | 3.90 (1.317) | 3.50 (1.826) | 3.20 (1.556) | 3.40 (1.297) | 3.40 (1.446) | 4.10 (.955) | 4.20 (1.181) | 3.90 (1.533) | 3.50 (1.301) | 3.50 (1.038) | 2.30 (1.436) | 1.70 (.791) | 40 |
| Fabric 2 | 3.10 (2.240) | 2.40 (1.516) | 2.70 (1.636) | 2.90 (1.722) | 4.40 (1.707) | 4.70 (1.636) | 4.40 (1.985) | 4.40 (1.516) | 4.40 (1.516) | 4.50 (1.038) | 1.50 (.679) | 2.50 (1.038) | 40 |
| Fabric 3 | 3.60 (1.374) | 4.00 (1.432) | 4.40 (1.215) | 4.20 (.883) | 3.30 (1.436) | 3.40 (1.128) | 3.80 (.883) | 3.40 (1.215) | 3.90 (1.236) | 3.00 (.906) | 1.30 (.464) | 2.10 (1.057) | 40 |
| Fabric 4 | 1.90 (1.533) | 2.90 (1.392) | 2.70 (1.814) | 3.10 (1.661) | 4.40 (1.928) | 5.10 (1.057) | 3.00 (1.109) | 2.50 (1.519) | 4.10 (1.464) | 4.00 (1.432) | 3.30 (1.506) | 3.50 (1.769) | 40 |
| Fabric 5 | 2.60 (1.706) | 1.90 (.955) | 3.40 (1.297) | 3.10 (1.598) | 4.40 (1.516) | 4.10 (1.661) | 3.20 (1. 800) | 3.20 (1.418) | 4.70 (1.203) | 4.90 (1.150) | 2.00 (1.198) | 2.50 (1.585) | 40 |
| Leather 1 | 3.40 (1.446) | 2.70 (1.363) | 3.40 (1.646) | 2.50 (1.649) | 3.30 (1.363) | 3.30 (1.572) | 3.30 (.911) | 2.50 (1.219) | 3.60 (1.128) | 4.10 (1.392) | 4.60 (1.823) | 4.70 (1.814) | 40 |

| | Rigidity | | Formality | | Fineness | | Softness | | Modernity | | Irregularity | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2D Mean (SD) | VR Mean (SD) | 2D Mean (SD) | VR Mean (SD) | 2D Mean (SD) | VR Mean (SD) | 2D Mean (SD) | VR Mean (SD) | 2D Mean (SD) | VR Mean (SD) | 2D Mean (SD) | VR Mean (SD) | n |
| Leather 2 | 2.00 (.784) | 1.90 (1.150) | 2.40 (1.297) | 1.90 (1.598) | 3.00 (1.359) | 3.90 (1.150) | 1.70 (1.114) | 1.50 (.679) | 4.00 (1.867) | 4.30 (1.363) | 5.70 (1.203) | 4.70 (1.977) | 40 |
| Leather 3 | 4.00 (1.633) | 3.90 (1.150) | 4.30 (1.814) | 3.80 (1.091) | 3.10 (1.464) | 3.70 (1.285) | 3.40 (1.707) | 3.80 (1.344) | 3.60 (1.128) | 3.30 (.648) | 1.90 (1.236) | 2.10 (1.464) | 40 |
| Leather 4 | 2.80 (1.091) | 2.70 (.792) | 2.80 (.883) | 3.30 (1.198) | 2.90 (.955) | 4.20 (1.181) | 3.90 (1.661) | 3.20 (1.091) | 3.10 (1.533) | 3.70 (1.285) | 3.90 (1.317) | 2.90 (1.945) | 40 |
| Leather 5 | 3.60 (1.516) | 3.40 (1.646) | 3.00 (1.502) | 2.90 (1.057) | 2.70 (1.698) | 3.60 (.928) | 3.30 (1.572) | 3.80 (1.091) | 2.80 (.608) | 2.80 (.883) | 3.50 (1.987) | 3.00 (.906) | 40 |
| Wood 1 | 4.10 (1.837) | 3.30 (1.977) | 2.50 (1.519) | 2.50 (1.219) | 2.60 (1.297) | 2.80 (1.344) | 2.20 (.833) | 2.30 (1.018) | 2.40 (1.128) | 2.40 (.810) | 4.90 (1.598) | 3.90 (1.892) | 40 |
| Wood 2 | 2.80 (1.344) | 2.90 (1.464) | 2.50 (1.377) | 2.20 (1.265) | 2.80 (1.091) | 2.90 (1.464) | 3.60 (1.766) | 3.40 (.928) | 3.00 (1.281) | 3.10 (1.464) | 4.70 (1.506) | 4.50 (1.826) | 40 |
| Wood 3 | 2.80 (1.911) | 3.00 (1.359) | 1.80 (.883) | 2.20 (1.265) | 2.10 (1.236) | 3.10 (1.533) | 1.80 (1.091) | 2.30 (1.285) | 2.60 (1.374) | 2.90 (1.392) | 6.60 (.672) | 5.80 (.883) | 40 |
| Wood 4 | 3.10 (1.236) | 3.00 (1.281) | 2.50 (.679) | 2.80 (1.488) | 2.40 (.810) | 3.30 (1.203) | 2.70 (1.436) | 3.10 (.841) | 2.80 (1.091) | 2.90 (1.236) | 5.10 (1.722) | 4.40 (2.085) | 40 |
| Wood 5 | 2.60 (1.033) | 3.30 (.791) | 3.20 (1.265) | 3.00 (1.109) | 3.60 (.810) | 3.60 (1.297) | 4.30 (1.506) | 3.30 (.911) | 3.60 (1.374) | 3.60 (1.128) | 3.80 (1.418) | 3.60 (1.823) | 40 |

### Section 6.3.1 Rigidity

According to the test results in Figure 6.7, 24 of the 35 materials showed strong rigidity in the 2D test. As shown in Table 6.5, from the scores after evaluation, it can be found that Metal 1 (brushed aluminium) is the most obvious material to feel rigidity in the 2D test (n = 40, M = 5.40, SD = 1.215). The material that can be strongly feel rigidity in the VR test is Stone 4 (plaster) (n = 40, M = 4.30, SD = 1.870). Metal 3 (polished steel) was selected as the material with weak rigidity property in the VR test (n = 40, M = 1.70, SD = 1.203). Of course, Fabric 4 (silk) scored the lowest value in the 2D test (n = 40, M = 1.90, SD = 1.533). No matter which viewing mode, it seems that gloss is an influencing factor, which will weaken users' judgment of rigidity.

### Section 6.3.2 Formality

Similar to rigidity, users also can perceive the feeling of formal in the materials in 2D viewing mode, accounting for 66% (23 materials). Plastic 5 (resin epoxy) and Paper1 (thick paper) scored the highest in the 2D (n = 40, M = 4.80, SD = 1.418) and VR viewing environments (n = 40, M = 4.80, SD = 1.742), respectively. This may be because the white colour can lead to the formal empathy of users. The lowest scores were obtained by Wood 3 (cedar) in 2D viewing (n = 40, M = 1.80, SD = .833) and Metal 3 (polished steel) in VR viewing (n = 40, M = 1.40, SD = .928), respectively. Unlike rigidity, Metal 3's smooth visual effect has caused users' dissatisfaction with the material format.

### Section 6.3.3 Fineness

Unlike the evaluation of the first two emotional standards, fineness shows different results, and the experience of 23 materials in the VR mode is clearer. As for the specific material scores, there are three kinds of materials that can make users feel fine in 2D tests, namely Fabric 2 (velvet) (n = 40, M = 4.40, SD = 1.707), Fabric 4 (silk) (n = 40, M = 4.40, SD = .928), and Fabric 5 (denim) (n = 40, M = 4.40, SD = 1.516). Among them, Fabric 4 (silk) is also the highest score in the VR test (n = 40, M = 5.10, SD = 1.057). On the other hand, it is difficult for users to experience fine feeling in Wood 3 (cedar) in 2D viewing modes (n = 40, M = 2.10, SD = 1.236) and Paper 4 (parchment) in VR viewing environments (n = 40, M = 2.60, SD = 1.374). The fabric materials with noticeable texture are endowed with intense fineness by the two devices, and the clear texture or complex texture effect becomes the basis for users' judgment.

### Section 6.3.4 Softness

22 kinds of materials can experience strong softness in 2D viewing mode. The judgment results of this dimension show that in the 2D test results, Metal 2 (painted copy) (n = 40, M = 4.80, SD = 1.682) and Leather 2 (snake) (n = 40, M = 1.70, SD = 1.114) represent the bi-polar of softness. Coincidentally, both Leather 2 (snake) and Metal 3 (polished steel) got the same score, is the lowest score in the VR test (n = 40, M = 1.50, SD = .679). Fabric1 (cotton) (n = 40, M = 3.90, SD = 1.533) is soft enough for VR testing. For the judgment of materials with higher softness, the 2D result seems to be dominated by colour, while the judgment of VR is obtained through texture effect. The materials with precise edges, corners, and obvious metal textures provide lower softness.

### Section 6.3.5 Modernity

VR provides gripping effects in modernity perception, and 21 materials have received higher scores. Plastic 4 (plastic fine sand grain) (n = 40, M = 5.20, SD = .992) played an extremely modernity role. However, Paper4 (parchment) (n = 40, M = 2.10, SD = .545) made it difficult for users to recognize modernity. The 2D test provided different results. Plastic 2 (rubber) (n = 40, M = 4.90, SD = 1.598) and Wood 1 (oak) (n = 40, M = 2.40, SD = 1.128) represent the highest and lowest degree of modernity. Users prefer to choose matte textures and dark materials in black and dark grey if they prefer the visual effect looks modernity. The texture attributes give users more space to imagine. The material selection of higher modernity is the same as that of delicacy, which is also related to material texture. On the contrary, more concrete plane materials often limit the imagination of users.

### Section 6.3.6 Irregularity

Although no statistically significant difference was found in irregularity, the comparison of material performance under the two devices is similar, 19 materials get higher score in 2D viewing mode and 12 materials in VR viewing mode. According to the test results, Wood 3 (cedar) has the highest irregularity score in 2D (n = 40, M = 6.60, SD = .672) and VR modes (n = 40, M = 5.80, SD = .833). The material with the lowest score is Fabric 3 (nylon) in 2D, Plastic 4 (plastic fine sand grain), and Paper 1 (thick paper) in VR. The scores of the three materials are the same (n = 40, M = 1.30, SD = .464). For irregularity, complex texture effects will disturb users' visual judgment, so such materials are often given high scores.

## Section 6.4 Discussion

This chapter discussed the interaction between visual features of different materials and users' perceptual experience. The traditional 2D and immersive VR viewing modes are used as the media of material presentation. In the evaluation scheme, participants judged the perceptual responses of 35 materials according to six emotional criteria: rigidity, formality, fineness, softness, modernity, and irregularity. The experimental results showed that the VR viewing mode could give participants more apparent judgment of material details and texture attributes, which substantially impact materials with texture-dominated emotional experience. Meanwhile, the 2D viewing mode is more effective for expressing the characteristics of plain surfaces. The evaluation results are helpful to the design evaluation that need to highlight perceptual features and enhance users' impression of specific product characteristics.

### Section 6.4.1 Stereo Vision Impact

The purpose of this study is to explore the perceptual cognition of users in the material wrapping environment through different viewing modes (VR and traditional 2D mode). According to the results, the two viewing modes are different for the single perceptual cognition of the same material in most cases. Among the six perceptual criteria, irregularity has no significant impact on the results of this study, which means that users' judgment of irregularity is not affected by VR viewing mode or computer-based visual effect. The reason is related to the meaning of the word "irregularity." Whether or not there is an immersive effect, the viewing device directly projects the appearance of the material itself. Whether the visual effect of the material is regular or messy determines the scoring result of irregularity.

In addition, according to the test results in Table 6.5, the interaction results between these emotional semantics and the users' emotional response are displayed. Intuitively, in the design evaluation, the traditional 2D viewing environment can better highlight the effects of rigidity, formality and softness. On the contrary, fineness and modernity emotional responses can be easily recognized and felt in VR. There is such a distinction that seems to be related to the connection between the texture of materials and KW. Taking delicacy as an example, we often think that perfect and fine materials can express the feeling of delicacy. This allows the user to focus more on the pattern details of the material texture. The 3D perspective provided by VR visually strengthens the bump and 3D effect of material texture. Users can use HMD to intuitively evaluate whether the detail of these 3D textures meets the delicacy. The test results of contemporary also supported this point. When we describe contemporary (section 6.3.2), we interpret this emotional response as a collection of words with particular styles. The design features expressed by these words are diverse. Therefore, how to better recognize and perceive the details of material texture is one of the keys that affect users' evaluation from contemporary. In the interview session, the participants' answers also confirmed this explanation:

"*The bump texture will affect the judgment of delicacy*."

"*The evaluation of delicacy will observe whether the texture has details or the harmony of colours*."

"*The contemporary evaluation will consider whether the characteristics of this material have been seen in works of art*."

This supports the previous research of Niu & Lo (2022). They believe that VR can provide users with more accurate judgment because VR can provide users with an environment for identifying material information. Gourishetti & Manivannan (2019) research also confirmed that users could make a more focused judgment because the visual noise provided by VR is less than that of traditional 2D viewing mode. Rhiu *et al*. (2020) believe that VR can provide better user performance than the traditional 2D viewing mode. Unlike VR, non-immersive viewing mode displayed the visual effect of a 3D model on a 2D screen. Therefore, on the one hand, the research results express the intensity of the semantic presentation of the two devices. On the other hand, it also emphasises that the human eye can directly recognize the 3D texture changes of materials through vision. However, when these 3D textures are presented on a 2D screen, the more intuitive performance effect of 3D is relatively lost. Unusual bumps or dents accompany some natural textures of materials. Participants cannot quickly judge the characteristics of materials with similar colours in the 2D test, but these details can be clearly found in the VR test. For those materials that prefer plane visual effects, the 2D display could highlight this effect. Therefore, in the design evaluation stage, if the designers have a clear need to meet the design requirements applicable to some scenes, they can choose different visual devices to present according to the design effect that the materials want to highlight.

### Section 6.4.2 Embodied Environment Impact

In addition to the influence of stereo vision provided by VR, the embodied cognition of participants is also one of the factors causing the experimental results. Compared with the traditional 2D viewing mode, the immersive feature of VR is the key factor of many studies choosing VR as a research tool. Although in the 2D test, participants viewed the material like 360 panoramas.

"*When I am wrapped in materials, the imaginary space will become more specific*."

"*I will bring the whole material (texture, colour, light sense) into the scene corresponding to the adjective to judge the matching degree. Once the same material is put into VR, individual differences will be reflected*."

"*VR is more sensitive to the recognition of polishing effect and gloss*."

"*When testing in 2D mode, you may feel that some materials are placed in the room unreasonably, and sometimes the score is very extreme. Nevertheless, when testing in VR, it feels that the environment looks real and reconsider the score under reasonable circumstances*."

"*I saw more details when I was wrapped*."

From the interview results, it can be found that the participants are in a specific environment and become very cautious and sensitive to the thinking and judgment of materials. Ching (2014) pointed out that the perception of the visual environment depends on the relationship between the material, texture, and other attributes of design elements and space. Franz *et al*. (2005) emphasised that the emotional perception of space triggered or affected the emotions and preferences of observers through the psychological dimension. This emotion is determined by culture, imagination, memory, thought, or previous emotional state. Emotion and experience are interdependent. When participants are in an immersive environment, the basis of evaluation is often judged according to the rationality of imagination.

## Section 6.5 Summary

With the trend of more efficient and intelligent industrial design, product design also improved user experience. When the product function is no longer the only design standard, designers and consumers add perceptual considerations to the product evaluation. At the same time, because the product's visual effect is often affected by the material appearances, designers must consider how comprehensive design elements such as materials and textures can meet consumers' emotional needs. VR has been skillfully used in design evaluation and has not entirely replaced the traditional 2D viewing mode. The research problem put forward in this study is how designers use appropriate equipment to present the design effect they want to express. This study explains the difference in users' emotional responses to material perception between immersive VR and non-immersive 2D viewing modes. According to the commonly used KW in current design and MDS, the perceptual criteria of the research are rigidity, formality, fineness, softness, modernity, and irregularity. A 3D space is built through the real-time rendering engine. Seven material categories and five materials are selected as the test stimulus. Participants were asked to use two viewing devices to observe the materials in the space and score according to the perceptual criteria. The results showed that participants used VR to score higher in evaluating fineness and modernity. Moreover, the 2D viewing mode can be more sensitive to rigidity, formality, and softness. There was no significant difference between the two viewing devices in irregularity. The embodied cognition and 3D perspective of VR immersion make participants judge the material and texture details more clearly. Extending this result to design practice, this study put forward some suggestions for designers to express the design effect in the future. When there are concave-convex or 3D textures on the surface of the displayed and presented materials, VR can identify these details more obviously, which helps deepen the fineness and modernity of the product vision. If designers pay more attention to the plane colour or pattern change, 2D viewing mode is more helpful, especially in rigidity, formality, and softness performance. These findings are especially applicable to design evaluations requiring immersion, such as automotive interior design, space design, etc.

Based on all the research in this thesis, the initial research validated that VR and 2D viewing modes can provide different perceptual feelings for users. This finding supports the feasibility of subsequent research and analysis of the perceived differences. For the material properties, the results showed that VR could support users in making a more refined judgment and recognition of material properties. That is to say, the users perceive better the minute changes of material properties under immersive viewing conditions. In terms of emotional aspects, VR is advantageous in signifying the effects induced by visual textures or details, while the 2D viewing mode is more effective for expressing the characteristics of plain surfaces.

# Chapter 7 Conclusion

## Section 7.1 Reflection to Research Hypothesis and Aims

Material perception is the process of experiencing visual cues on material appearance. These visual cues form retinal images, including the shape, appearance characteristics, and other visible cues of materials, which are transmitted to users through the visual system for identifying and feedback on the appearance of materials or products. However, accurately defining the perceptual cues of material visualisation is challenging. It is difficult for users to directly describe the relationship between the perceptual preferences of materials and appearance characteristics in a visual context. Therefore, this requires visualisation tools to show the expected visual effects and clearly express the digital context of material appearance through simulation and rendering technology.

Therefore, the main research questions to promote the above thinking are:

> "*Do users perceive material appearances differently under VR viewing and traditional 2D viewing conditions? And more specifically, how do those differences manifest through measurable perceptual and emotional responses invoked by materials presented in VR and 2D displays?*".

Furthermore, critical insight is that in the process of material perception, the physical properties at the objective level determine the material appearance and finishing process. The subjective perception of materials is often inseparable from product semantics and emotional value. Therefore, based on the material perception process mentioned by Fleming (2017), this study focuses on the differences in users' perception experience of materials, judgment and recognition of material properties, and emotional responses under the two viewing modes. The research outcome is shown in Figure 7.1.

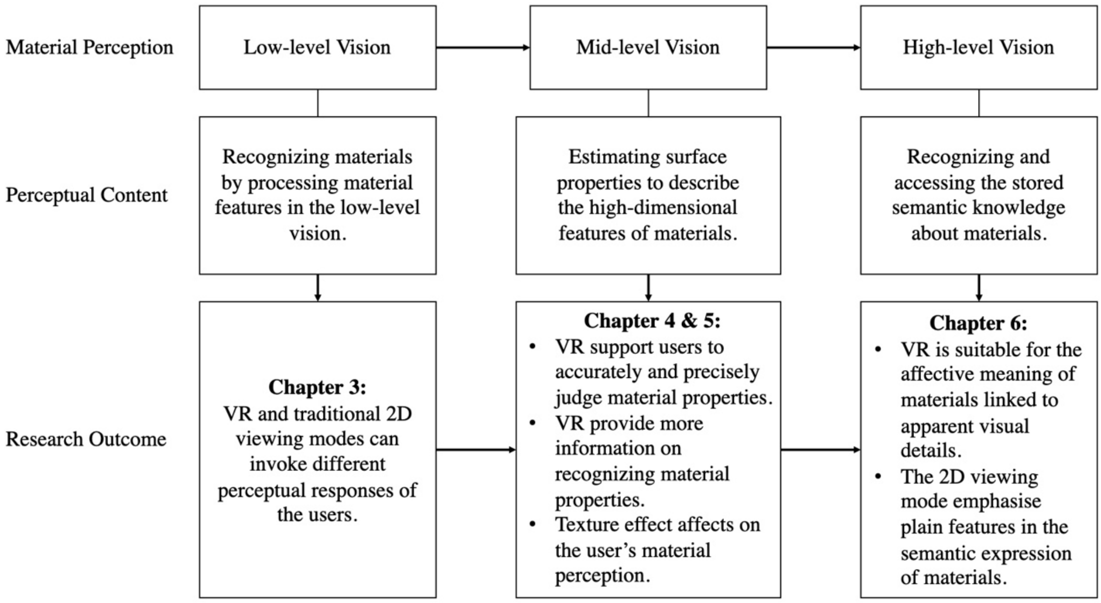


*Figure 7.1. The Research Outcome of Material Perception in Virtual Environments.*

In the low-level vision, the preliminary research evaluates the users' perception towards the simulated material visualisation under VR and 2D viewing mode. Reflecting on the first research aim, this study observed that the users' evaluation of the visual content presented by VR devices was closer to the realistic materials, based on the immersive visual experience. Similarly, relying on the analysed results, the thesis has validated the first hypothesis, that is, VR and traditional 2D viewing modes can invoke the users' different perceptual responses.

Considering that mid-level vision uses retinal images to infer and estimate material properties, the thesis took the psychophysics approach to establish the perceptual scale of material properties, which were used as the test samples. According to the accuracy and precision analysis of matching results, the study found that subjects can maintain a higher level of correct judgment in VR viewing mode compared with the 2D test. In addition, the research further explored and measured the comparison of perceived differences in material properties between the two viewing modes by the psychophysics approach. The results of these two studies confirm the second hypothesis. Furthermore, texture mapping is also adopted in the material evaluation as a 'material property'. The analysed results respond to the third hypothesis that texture mapping affects participants' perception and recognition of roughness. The findings reflect the second research aim, specifying and measuring the relationship between the perceived differences and the properties of rendered material under VR and traditional

2D viewing conditions. For the material properties, the results indicated that VR could support users in making a more refined judgment and recognition of material properties. In general, the users perceive better the minute changes of material properties under immersive viewing conditions.

As for the high-level vision, the study answers the fourth hypothesis about users' emotional response to material perception depends on the viewing modes in virtual environments. At the same time, the study finding also reflects the third research aim of the thesis. This study observed that the VR viewing mode is more suitable for highlighting or emphasising the material details, such as material texture. Meanwhile, the 2D viewing mode can effectively provide the semantic expression of material features, such as plane images and colour. Most importantly, the reason for this perceptual difference is, on the one hand, the stereoscopic perspective provided by VR. On the other hand, the embodied cognition of users in an immersive environment has also become an influencing factor.

Based on the summary of the above research, this study discussed how these results can be inspired and reflected in future design activities in the next section.

## Section 7.2 Contribution of this Thesis

Introducing user experience and feedback into the design evaluation process is beneficial for designers to optimize the design scheme. Buckingham *et al*. (2009) believed that users' perception of material information consists of visual neural circuits (the ability to recognize materials based on visual images) and their previous experience and knowledge. Therefore, the display devices are used to analyse the differences in visual images to obtain the users' perceptual results of materials. This approach leads to different findings on the differences in material perception between VR and traditional 2D viewing modes: the two viewing modes can invoke users with different visual experiences (Chapter 3); VR can more effectively judge and identify changes in material properties (Chapter 4 and Chapter 5); the display devices can provide a more effective presentation for expressing emotional responses expressed by different materials (Chapter 6).

Therefore, this section focuses on considering design tools in the evaluation process and provides insights on equipment applications for future design links. In this section, this study established the relationship between these findings and the development of material visualisation in future design activities and supplement the contribution of the research findings to reflect the perceived effect of material visualisation in a VR environment.

Specifically, the contributions of this thesis are summarised as follows:

> *Contribution 1: Validated the difference between users' perception of materials in VR and traditional 2D viewing modes.*

This thesis validated that users experience different material perceptions in VR and traditional 2D viewing modes. On the one hand, due to the isolation of computer screens from 3D models, users clearly aware that the content they observe is virtual in the 2D viewing mode. On the other hand, HMD also causes a device gap experience, and users still realise themselves in the virtual world. However, VR is described as a hybrid of realistic and imaginary media (Siess et al., 2018). The imagination in VR features relatively weakens users' objective and rational thinking (Idris & Ahmed, 2020). VR allows users to participate in computer-generated virtual environments to experience and perform tasks (Tachi, 2013; Maach et al., 2018). Consequently, there is a boundary between this immersive environment and the traditional 2D viewing mode, which differs from established media's perception habits.

*Contribution 2: Derived the perceptual scale for both VR and traditional 2D viewing modes by psychophysics.*

The rendering engines on the market provide predefined material libraries and allow operators to adjust the numerical material parameters of basic controls to render VP and materials appearance. However, the adjustment of these parameters is regular (arithmetic progression, value from low to high), and it needs experienced designers to achieve the expected effect, which is unfriendly to inexperienced individuals. Users focus on their visual perceptions rather than specific parameter. This thesis gave supporting evidence by the established perceptual scale that the perception between the observer and the change of material properties is not linear. Therefore, this finding indicates that designers should consider perceptible material properties to avoid invalid adjustment of parameters. It also provides an interesting perspective for the material editing interface in the developing rendering engine. Specifically, the developing interface presents an effective material attribute editing and the adjustment mechanism rather than a unified scaling mechanism with the rule of numerical value. Such interface development will help improve design tools' practicability and effectiveness, not just academic exploration.

*Contribution 3: Confirmed users could perceive more material information under the VR viewing mode.*

The importance of visual information to material visualisation cannot be understated. The study found that observers can effectively identify and obtain the useful information on material appearance under VR viewing mode. VR provides a refined visual environment for judging material information so that the observer can recognise more changes in material properties. Fleming (2017) once pointed out that the visual system relies on light illumination to supplement local information about objects and materials in the environment. As early as Marlow et al. (2012) put forward similar views. From the perceptual perspective, human stereo vision is formed with two slightly shifted physical images projected on the two retinas. VR's HMD achieves this visual parallax by delivering different image frames via the left and right lense. This effect of binocular parallax helps the observer experience depth perception (Buxton et al., 2000; Ni et al., 2006; Shao et al., 2012). However, just as the VR applications continue to pursue more natural human-computer interaction, depth perception emphasises the effect of people observing 3D models avoid cognitive burden for users. Compared with the traditional 2D observation mode, VR uses the more unrestricted perspective provided by the HMD to help identify these minute changes among material properties. Immersive VR environment assists in intuitive surface modelling and sculpture modelling, which is essentially different from the display mode of a 2D plane image. Therefore, this thesis emphasises that the influence of the depth perception provided by binocular parallax on material properties.

*Contribution 4: Reviewed the perceptual effect of material attributes based on texture mapping through VR and traditional 2D viewing modes.*

After continuous training, the human visual system can form cognition by recognising material characteristics (Ashby & Johnson, 2013). The thesis showed that the materials' texture mapping would affect or interfere with the observers' perception. The research also explained that the depth effect formed by the textures' bumping effect influence the users’ resolution of material properties (such as light spots). When designers simulate the material appearance, they should ensure that the materials' texture effect do not affect the presentation of material properties to obtain the routine evaluation and feedback. This correlation between material texture and physical properties promotes the comprehensiveness of the design simulation effect. Chapter 6 pointed out that the texture can set off the emotional properties of materials under different viewing modes. Designers combine perceptual semantics with the understanding of material characteristics by VR and traditional 2D viewing modes and enrich the understanding of the relationship between emotion (perceptual description) and coding (material simulation) to improve the user experience.

*Contribution 5: Analysed the users’ embodied cognition on the perceptual effect of materials in VR and traditional 2D viewing modes.*

The explored research includes the impact of embodied cognition on participants. Compared with the traditional 2D viewing mode, VR can present embodied visual stimuli along with 3D space (Wilson & Soranzo, 2015). To avoid causing users' cognitive burden, VR can promote the communication process between stakeholders through intuitive embodied cognition. Especially for stakeholders with different backgrounds and preferences (Roupé et al., 2014).  VR and traditional 2D viewing modes play different roles in presenting the emotional characteristics of different materials. This means that the display tools reflects the value of material properties. Users set up their impressions, feelings, and needs of products reflected by the viewing modes in the final product appearance. On the contrary, designers can quantitatively identify and adjust visual stimuli to make products more user-friendly.

This thesis aims to encourage designers to use appropriate visualisation tools to express the significance and value of materials and drive the evaluation and development of subsequent products. Whether it is the traditional 2D viewing mode or immersive VR experience, the purpose of the application is to express materials and provide designers with clear and feasible design rules.

## Section 7.3 Limitations

Reviewing the research process of this thesis, the thesis listed the limitations as follows:

1. Colour. As another influencing factor of product appearance, material colour greatly influences some emotional attributes on design evaluation, such as visual temperature. So far, many studies on the potential influence of colour on the perception of material properties are still controversial (Cant & Goodale, 2007; Xiao & Brainard, 2008; CavinaPratesi *et al*., 2010a, 2010b; Wendt *et al*., 2010; Chadwick & Kentridge, 2015). Kentridge *et al*. (2012) believed that when individuals observe materials, the areas where material properties activate the cerebral cortex are different from the areas where vision responds to colour. To avoid the cognitive burden of random colour and colour removal on users. In the test phase of Chapters 4 and 5, the material colour in line with the basic cognition is selected, such as adding a yellow effect to metal. Although in general, the observers' judgment of material properties shows varying degrees of acceptance. Nevertheless, the influence of colour cannot be ignored.

2. Restrictions on texture and material category and display scenarios. In Chapters 3 and 4, only opaque and non-textured materials are selected to avoid the influence of texture mapping. Ho *et al*. (2008) proved that the effect of material surface texture could significantly affect the constancy of gloss. However, texture mapping is one of the commonly used methods of material expression. Although the results of Chapter 5 found that texture mapping could affect the perception of material properties, whether in VR or 2D viewing modes. The implementation and analysis of this texture effect on the matching task in Chapter 4 remain to be further discussed.

In addition, simulating complex optical effects in transparent and translucent materials is also a challenging task. The material perception discussed in this study focuses on opaque materials. It seems a comprehensive but arduous task to add transparent and translucent materials and analyse the perceptual differences between the two display devices.

Furthermore, the selected display environment in this thesis to presenting visual stimuli is based on the default setting of UE4. The consideration of this selection is to avoid disturbing visual factors. However, the environmental scenario of material placement should be further verified as a consideration.

3. Selection of test object. Most of the materials in the rendering engine are presented on the sphere to show all possible surface orientations towards to the observers. At the same time, the convexity spheres in interactive rendering also eliminate the influence of self-shadowing and interreflection. Early Vangorp *et al.* (2007) proposed to evaluate the objects' influence on the perception of material properties. Some studies indicated that the 3D shape of the virtual model could affect the gloss perception alone. Multiple authors suggested using irregular objects for testing (such as the objects placed in Chapter 6). Of course, other discussions believe this perception effect is closely related to lighting. A study by Nefs *et al.* (2006) found that the surface undulation effect perceived by materials is caused by lighting rather than surface characteristics. However, the thesis must admit that the shape of the test object may become the influencing factor of material perception, which needs to be further proved in future tests.

4. Selected Devices. This study selects VR HMD and a gaming laptop to test VR viewing mode and traditional 2D viewing mode, respectively. Although this is representative of the design application, it has to be acknowledged that the test results of participants in 2D viewing mode may be affected by the display size.

## Section 7.4 Future Investigations

Future work should focus on enriching material categories and considering more extensive content combining physical and emotional properties of material perception in the VR environment. Based on the results of Chapters 3, 4, 5, and 6, a more comprehensive comparison of material categories is proposed, which provides a standardised way for designers to simulate materials. Another point of interest is to utilise the known test results to establish a relationship between the physical and emotional properties of material perception in the VR viewing mode. Applying these findings to the design content helps designers quickly select materials and realise the expected material visualisation.

In addition, a direction worth expanding is that there are still perceptual differences between the material perception of VR and the actual physical world. This thesis tests aimed at the visual effect provided by the material under the rendering engine. Among them, the thesis mentioned multiple times that VR can help users "accurately" judge the material information, which is also based on the virtual environment. However, more investigation is needed to explore the gap between VR and the real world and how VR realises the realistic perception of users. This work contributes to achieving more realistic visual effects for VR. The author hopes this work can inspire researchers on material design expression and VR visual experience to provide a more novel experience for the future design environment.

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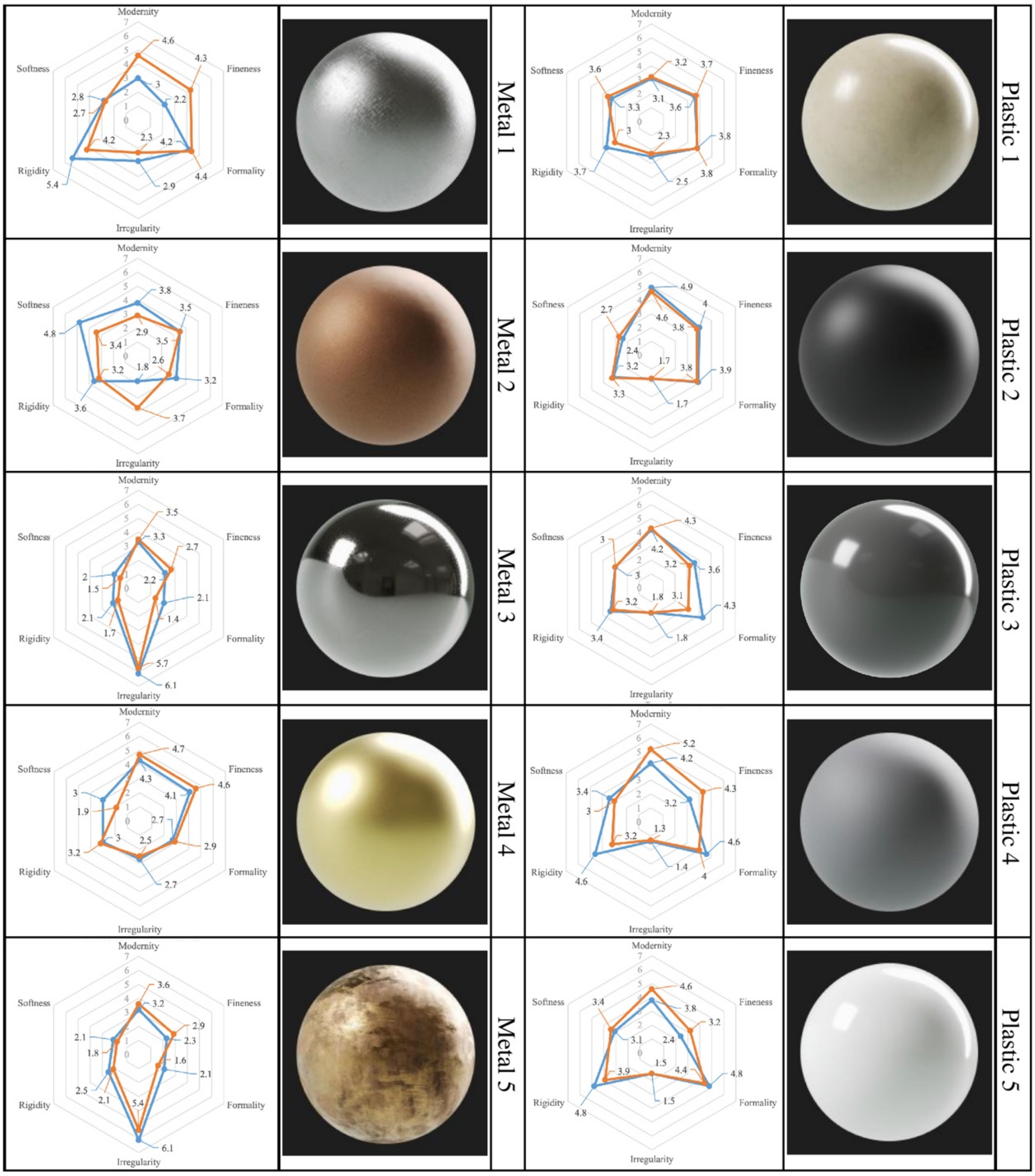
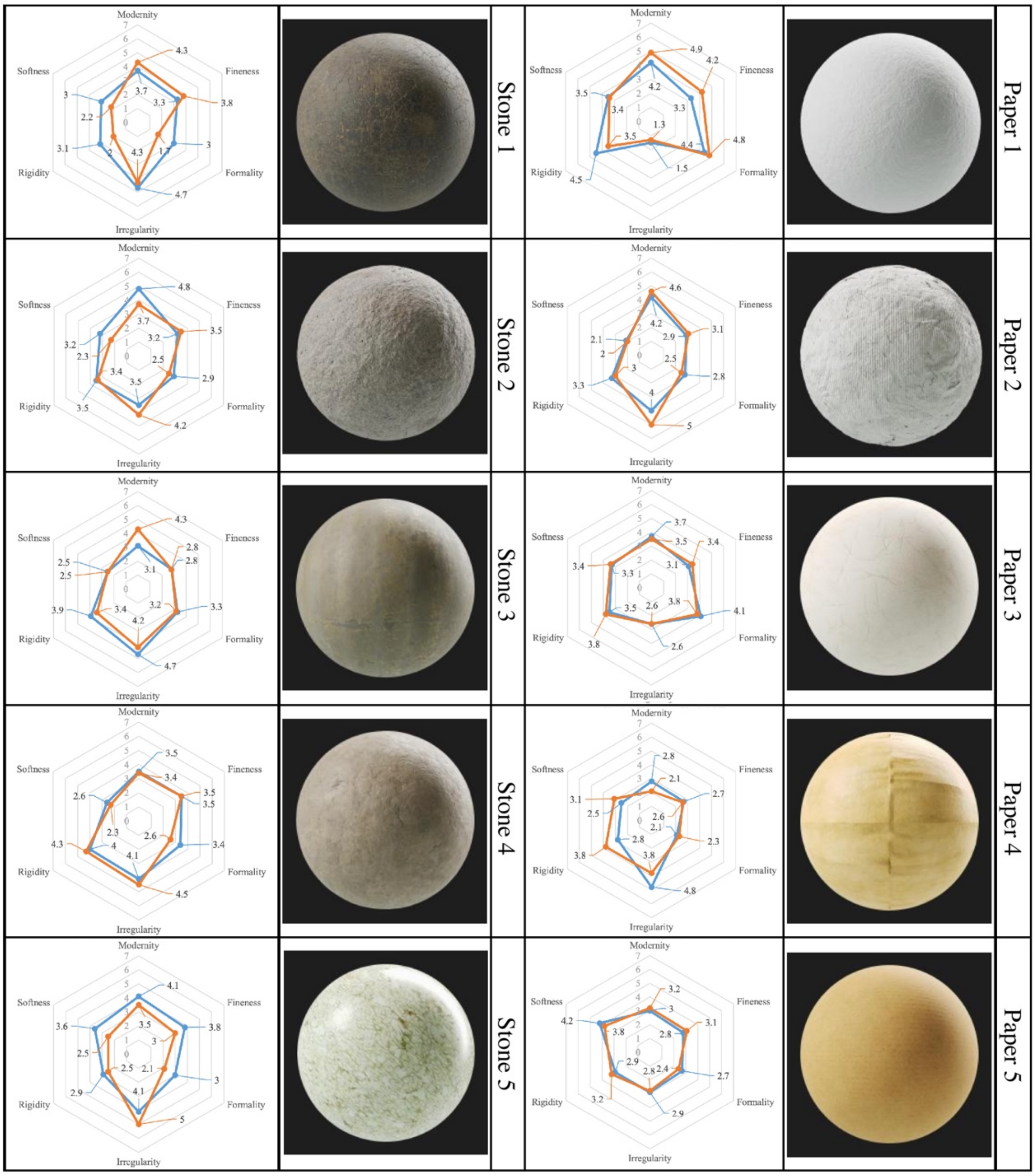
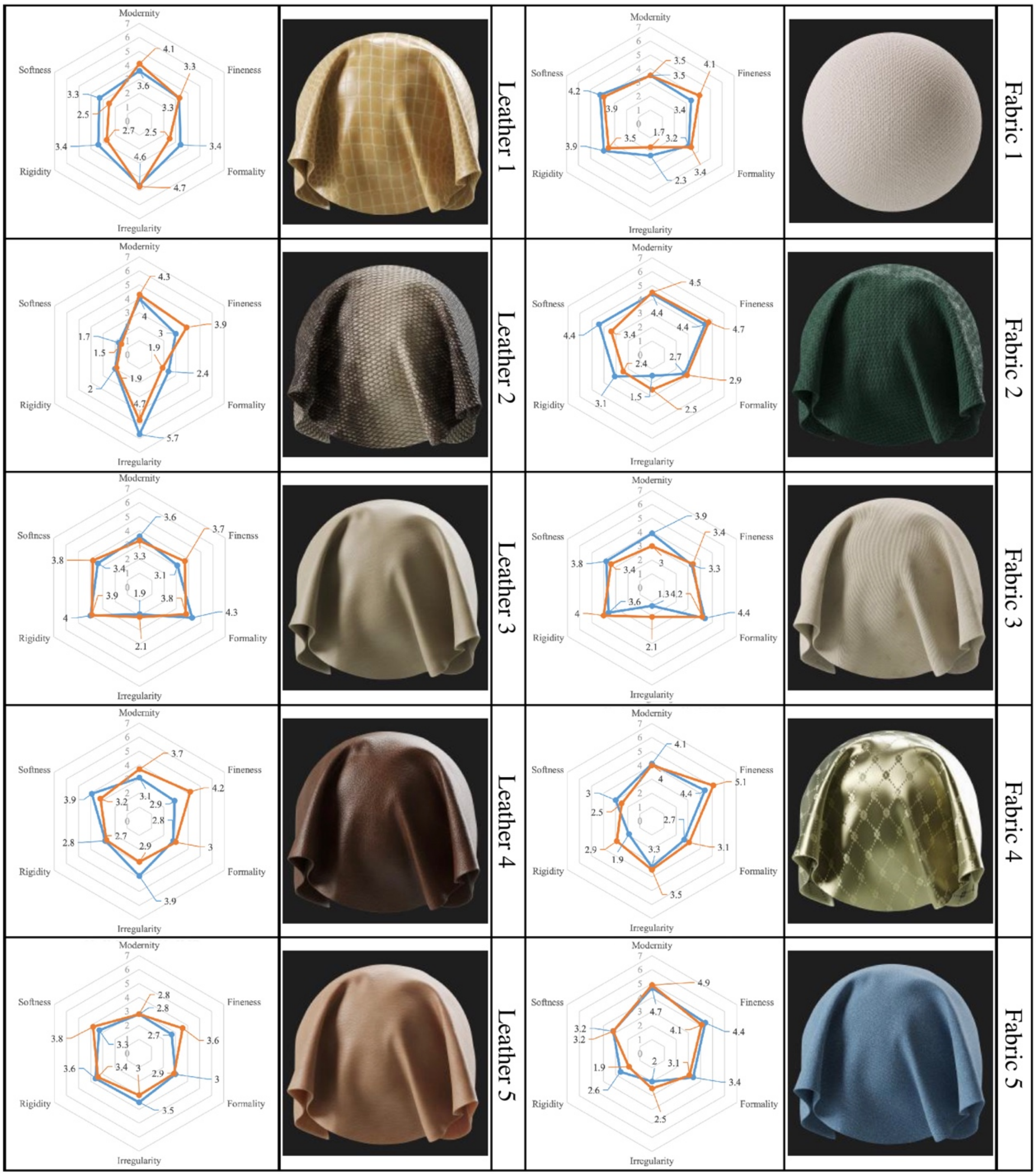
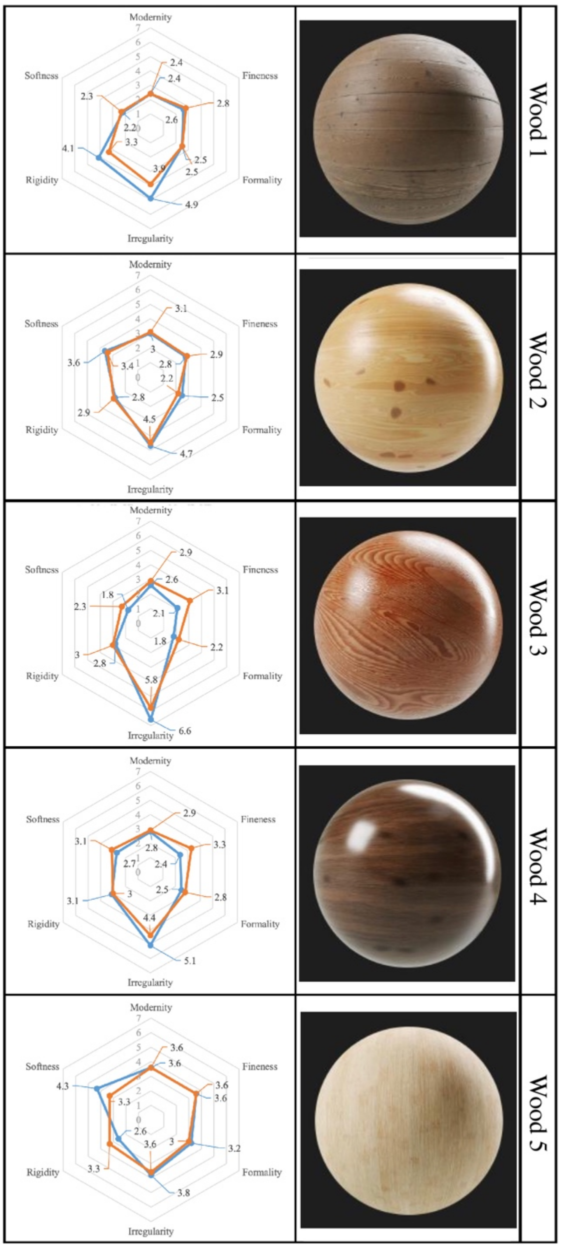
# Appendix

*Appendix 1. Radar chart of corresponding test material.*




Stone 1
Paper 1
Stone 2
Paper 2
Stone 3
Paper 3
Stone 4
Paper 4
Stone 5
Paper 5
Modernity
Fineness
Formality
Irregularity
Rigidity
Softness


Modernity
Fineness
Formality
Irregularity
Rigidity
Softness
Leather 1
Leather 2
Leather 3
Leather 4
Leather 5
Fabric 1
Fabric 2
Fabric 3
Fabric 4
Fabric 5


Modernity
2.4
2.4
Softness
Fineness
2.3
2.8
2.6
2.2
4.1
3.3
2.5
3.9
2.5
Rigidity
Formality
4.9
Irregularity
Wood 1
Modernity
3.1
Softness
Fineness
3
2.9
3.6
3.4
2.8
2.2
2.8
2.5
2.9
Rigidity
4.5
Formality
4.7
Irregularity
Wood 2
Modernity
2.9
2.6
Softness
Fineness
3.1
1.8
2.3
2.1
1.8
2.2
3
2.8
Rigidity
5.8
Formality
Irregularity
6.6
Wood 3
Modernity
2.9
Softness
Fineness
3.1
2.8
3.3
2.7
2.4
3.1
3
2.5
2.8
Rigidity
4.4
Formality
5.1
Irregularity
Wood 4
Modernity
3.6
3.6
Softness
Fineness
4.3
3.6
3.3
3.6
2.6
3
3.6
3.2
Rigidity
3.3
Formality
3.8
Irregularity
Wood 5