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The Interplay of Subjective Quality Evaluation, Prototyping Technologies and the User's Technology Acceptance

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Abstract

Subjective product quality is a fundamental aspect to maintain a high level of user acceptance and to provide a good user experience. Prototypes can be used to evaluate subjective product quality in early design phases. We conducted an empirical study to examine the influence of different (re)presentations of prototypes determined by the chosen technology (2D image, VR, AR, 3D print) and the user's technology acceptance. Based on the results we recommend 2D images as most reliable for evaluating subjective product quality.

Keywords: empirical studies, emotional engineering, prototyping, subjective quality, technology acceptance

1. Introduction

1.1 Prototyping in the context of subjective product evaluation

In order to maintain a high level of user acceptance and to provide a good user experience, products need to satisfy no longer only objective but especially subjective quality demands of users. Following Kurosu's model of quality characteristics (2015), usability, reliability, cost, safety, compatibility and maintenance are assigned to the objective quality, whereas satisfaction, pleasure, joy, beauty, attachment, motivation and value contribute to the subjective quality of a product.
The assessment of subjective product quality results from product perception and its evaluation. In this context, according to Woodworth's (1929) established S-O-R model, one or more observable stimuli (S) lead to mental processes in the organism (O) which in turn evoke an individual response (R) from a person. The stimuli are perceived through the human's sensory system (cf. Scharf, 2000), whereas their dominance varies between different stages of user-product interaction. While vision is most important in the beginning, touch becomes important during long-term product use (cf. Fenko *et al.*, 2010). Crilly *et al.* (2004) state that product evaluation can be understood as an expression of the user's product perception. Thereby, the assessment of subjective quality remains challenging as their above-mentioned characteristics are sometimes volatile, intangible and hidden inside the user's mind (cf. Desmet and Pohlmeyer, 2013; Schröppel and Wartzack, 2018). However, recent research provide promising approaches to measure single aspects of subjective quality. AttrakDiff, for instance, is a survey developed by Hassenzahl *et al.* (2003) that measures the attractiveness and hedonic quality of a product. Zöller and Wartzack (2017) provide impressions profiling to measure the user's attitudes towards a product. Within Kansei Engineering studies, semantic differentials are used to evaluate product perception (Nagamachi and Lokman, 2011). Minge *et al.* (2016) introduced a modular

questionnaire to capture different components of user experience like visual aesthetics, status or emotions.

The consideration of subjective quality characteristics should happen, analogously to all fundamental design decisions, in the early phases of product development as design changes usually become more expensive and difficult as the design process continues (cf. e.g. Pahl *et al.*, 2007). By using prototypes, it is possible to investigate how the product will affect the user early and throughout the whole design process (cf. Dieter and Schmidt, 2013). Even though there is still no common definition for a prototype in literature (Jensen *et al.*, 2016), it can be broadly understood as ‘an approximation of the product along one or more dimensions of interest’ (Ulrich and Eppinger, 2007). Due to the intended purpose of a prototype, an appropriated (re)presentation has to be chosen. As mentioned before, visual appearance is fundamentally important for product perception and thus for subjective quality evaluation. Therefore, prototypes do not have to be fully functional in this context but need to (re)present the form and shape of a product adequately. Canuto da Silva and Kaminski (2016) differentiate between virtual and physical prototypes and provide an overview of different prototyping technologies in terms of their realisation. Thereby, virtual prototypes can, for instance, be developed with computer aided design / engineering techniques (CAD / CAE) using virtual or augmented reality (VR / AR) to present them in an immersive or semi-immersive 3-dimensional application (e.g. Stylidis *et al.*, 2019). Alternatively, these can also be displayed as spatial models in 2-dimensional images. Physical prototypes can be created with rapid prototyping such as 3D printing (Canuto da Silva and Kaminski, 2016).

Aiming for the most realistic and reliable evaluation of subjective product quality, the product developer has to choose between different prototyping technologies. In this context, it is important to understand that a person’s evaluation of a product is influenced by the applied prototyping technology due to differences in product appearance and the user’s acceptance of the used prototyping technology. In terms of product appearance, the discussion of (re)presentation of prototypes is nothing new. Diefenbach *et al.* (2013) compared, for instance, text, comic story, picture story, comic animation and video representation of a product concept showing significant differences in product evaluation. Stylidis *et al.* (2019) examined the assessment of perceived quality of different toaster designs via VR and a desktop system showing good usability for both technologies. However, these studies focus only on selected prototypes, use different measuring instruments and vary in the subject of observation which makes the studies hardly comparable with each other. In addition, various other studies deal with the general comparison of different technologies for specific tasks (e.g. Castronovo *et al.*, 2013; Pontonnier *et al.*, 2014) not addressing subjective product quality at all.

Besides product appearance, the user’s acceptance of prototyping technologies may influence the evaluation of subjective product quality. In this context, acceptance is understood as the concrete attitude towards a technology and the associated acceptability (Dethloff, 2004). Various acceptance models can be found in literature like the ‘unified theory of acceptance and use of technology’-model by Venkatesh *et al.* (2003) or the ‘task-technology fit’-model by Goodhue and Thompson (1995), each indicating different influencing factors for the acceptance judgement. Thereby, Schreiber (2020) differentiates between system and user characteristics. As such, user characteristics include, for instance, a person’s technology affinity or playfulness whereas system characteristics contain e.g. experience or utility with the system. It can be assumed that the manifestations of these characteristics can distort the subjective quality evaluation. Especially during immersive applications like VR/AR, the experience between human and system varies affecting product evaluation (cf. Kollmann, 1998). In the context of consumer purchase decisions, for example, it was shown that a playful VR user interface can increase consumers’ preference for hedonic product benefits (e.g. an elegant and attractive design) (Kang *et al.*, 2020). However, the extent to which technology acceptance affects the subjective evaluation of a product while using different prototyping technologies, i.e. different (re)presentations of products, has not yet been investigated in sufficient depth.

1.2. Aim and research questions

To enhance a more realistic and reliable evaluation of subjective product quality in early design phases, the present contribution addresses the above-mentioned deficits and aims for further

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examining the interplay of subjecteive quality evaluation, prototyping technologies and the user's acceptance of prototyping technologies. Therefore, an empirical study was conducted including the evaluation of three products (vase, knife, water sprayer) each presented in VR and AR, as a 3D print, as a 2D image showing a spatial model and as an original physical product. Two main research questions (RQ) are focused on:

1. Do different forms of product (re)presentation, which is determined by the used prototyping technology, influence subjective quality evaluation of prototypes and which of them provide the most realistic image of a product's subjective quality?
2. Does a person's technology acceptance influence the subjective quality evaluation of a prototype?

2. Methods

2.1. Study design and measuring instruments

To answer the research questions, an empirical study was conducted using a mixed methods approach (see Figure 1). Within a lab session, the participants experienced different prototypes and technologies as well as the physical products. The subjective quality of the prototypes / physical products as well as the acceptance of the used prototyping technologies were captured via quantitative questionnaires. Final technology ranking was conducted via guided interview (interview technique according to Smith and Albaum, 2005). As the study took place in Germany, the study material was provided in German.

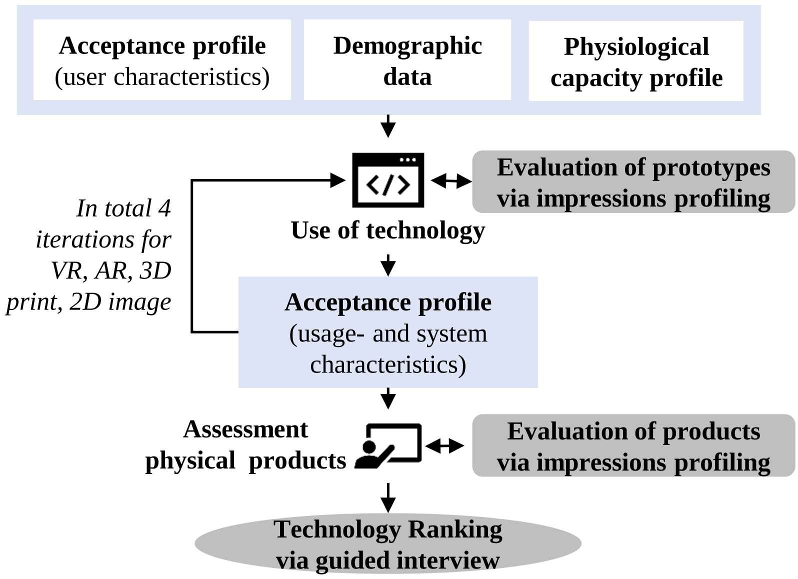

Figure 1. Procedure of study

Beginning with the collection of individual information about the participants, basic demographic data (age, gender and educational level) and the participant's physiological capacities of their basic human senses are assessed as these could determine the interaction with different technologies. Therefore, physiological capacity profiling by Schröppel *et al.* (2019) was adapted capturing the participants ability of vision, hearing, smelling, touching and their sense of balance using Semantic Differentials with 7-point-scale. On the other hand, an acceptance profile that addresses the user characteristics was queried to assess the general technology acceptance independent of the applied prototyping technology. The acceptance profile (user) consisted of six different aspects resulting in 15 different items, i.e. statements, that were rated from 'does not apply at all' to 'fully applies' on a 7-point Likert scale: Technology affinity (queried with 4 items); True innovativeness (queried with 2 items); Visual information processing (queried with 2 items); Need for haptics (queried with 2 items); Personal playfulness (queried with 2 items); Importance of aesthetics and visual attractiveness (queried with 3 items). The items are based on Schreiber (2020) and Schlohmann (2012).

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Afterwards, the participants were shown the three prototypes using the four different technologies VR, AR, 3D print and 2D image one after the other. The subjective quality of the prototypes was assessed via questionnaire straight after observation. Therefore, as part of subjective quality, the in section 1.1 mentioned impressions profiling by Zöller and Wartzack (2017) was used capturing the five impressions aesthetic/unaesthetic, high-quality/low-quality, modern/traditional, innovative/conservative, elegant/massive via 7-point scale using Semantic Differentials. After finishing the observation of the three prototypes with one technology, an acceptance profile concerning usage and system characteristics was assessed. Analogously to the user characteristics, the usage and system characteristics are based on Schreiber (2020) and Schlohmann (2012) and contain 10 items for four aspects: Ease of use/behavioural control (queried with 2 items); Benefit/relative advantage/benefit through technology (queried with 3 items); Perceived pleasure (queried with 3 items); Experience (queried with 2 items).
To avoid carry-over or repeated-measure-effects (cf. e.g. Asch, 1946; Carbon and Leder, 2005), a full factorial design was used that ensured a different order of the applied technologies and of the products considered per technology. 24 participants were recruited to cover each combination once. After assessing the different prototypes, the original physical products were assessed using the same impressions profiling as before. Lastly, the participants had to rank which technology was the most pleasant to use and were asked to give insights whether they were disappointed by any technology.
Clarity and correct understanding of the questions were confirmed by a preliminary study. As the study design required the participants to be present in person, protective measures had to be obeyed due to the ongoing SARS-CoV-2 pandemic. Thus, the participants needed to sanitise their hands regularly, keep their distance from the study leader and constantly wear a mask. Physical prototypes / products and technology devices were sanitised after each participant. As additional precautionary measure, vulnerable groups (e.g. elderly) were excluded as participants.

2.2. Product demonstrators

To provide a comprehensive comparison, three products with different levels of interaction and complexity were chosen: a vase, a water sprayer and an ergonomic knife (see Figure 2 for overview).

Figure 2. Product demonstrators as (real) physical products and 2D/3D/VR/AR prototypes (left) as well as an example of the AR and VR setup including its virtual room (right)

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The vase (from LSA International) represents a low complexity with a low level of interaction whereas seeing is the main stimulus of product perception. The ergonomic knife (from NRS Healthcare) and the water sprayer (from EFALOCK Professional Tools GmbH) have a higher degree of interaction. Thereby, besides seeing, touching is a central stimulus in product perception. Complexity is slightly higher for the water sprayer than for the knife as it contains more functionality. Preliminary to the study, the original products purchased on the market were remodelled in 3D CAD via reverse engineering using PTC Creo Parametrics (v.6.0.2.0). 2D images were created using the software's rendering studio. The virtual models were visualised in AR through the software's own interface using the VUFORIA VIEW app. The participants were given an 11" iPad Pro with which each virtual model was displayed after scanning a QR code in the room. For a VR based visualisation, an immersive environment (enclosed space of 4x4 metres with bar table on which model is placed) was built using Unreal Engine (v.4.22.3). The rendered scene is displayed via Steam VR using the HTC VIVE Pro direct-view head-mounted display. The Stratasys F370 printer and SCA3600 washing station were used to produce the 3D printed prototypes. The vase could be printed as one solid object. The knife consisted of two parts, which were assembled afterwards. The water sprayer also consisted of several individual parts, whereby a functional integration of pressing the trigger was realised by using a spring.

2.3. Data analyses

Descriptive statistic was used to classify the participants of the study demographically and to identify possible determinations in technology use depending on the participant's physiological capacity. To assess whether different forms of product (re)presentation influence the subjective quality evaluation of prototypes and which of them provide the most realistic image of a product's subjective quality (RQ1), a paired t-test was conducted. For each product, the evaluation of the prototype was compared with the evaluation of the physical product. The evaluation was divided according to the five examined impressions. With four applied technologies resulting in four different (re)presentations of prototypes as well as three different products and five impressions as measurable variables of subjective quality, 60 comparisons were examined (60 t-tests with n=24, df=23). In this context, few significant differences in the evaluation indicate a good representation of the real product. A *p* level of 0.05 or lower was interpreted as significant.

Furthermore, to assess whether a person's technology acceptance influences the subjective quality evaluation of prototypes (RQ2), a correlation analysis was conducted. Thereby, technology acceptance in terms of user characteristics was compared with the deviation of the evaluation between prototypes and real products considering the mean values over all impressions for each product separately (n=72). In addition, technology acceptance in terms of usage and system characteristics was also compared with the deviation of the evaluation between prototypes and real products considering the mean values over all impressions for each product separately (n=72). Thereby, both the deviation of subjective quality and the usage and system characteristics needed to be considered for each technology separately (e.g. deviation of VR and real product (VR/Real) with VR acceptance; deviation of 2D and real product (2D/Real) with 2D acceptance etc.). Using the Pearson correlation coefficient *r*, a *p* level of 0.05 or lower was interpreted as significant. Lastly, to evaluate the ranking of the applied technologies, the arithmetic mean as well as the frequencies of the ranks are examined. All statistical analyses were completed using Microsoft Excel and the statistical software SPSS (v.26).

3. Results

3.1. Participants

24 persons participated in the conducted study (63,5% male, 36,5% female, 0% diverse). Age distribution was homogeneous with 91,7% participants between 20 and 29 years and 8,3% between 30 and 39 years. All participants have a high level of education (A-Levels or higher). Analysing the physiological capacity profile, no participant showed deficits that would negatively affect their use of technology or product perception.

3.2. Impact of prototype (re)presentation on subjective product evaluation

60 paired t-tests were conducted identifying significant differences in subjective product evaluation for prototype (re)presentations and physical products. Table 1 summarises the resulting *p*-values of the t-tests while highlighting those being significant on the level below 0.05 and 0.01.

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Table 1. Resulting p-values from t-tests considering impressions per technology and product

Impressions	2D image	3D print	AR	VR	Product
aesthetic/unaesthetic	**.046***	.241	**.014***	.343	Vase
	.705	.118	.062	**.016***	Water sprayer
	.188	.750	**.001****	**.000****	Ergonomic knife
high-quality/low-quality	.088	**.000****	**.000****	.095	Vase
	.218	**.024***	**.001****	**.020***	Water sprayer
	.147	.096	.057	.084	Ergonomic knife
modern/traditional	.314	.116	**.006****	1.000	Vase
	.062	**.010****	.087	**.004****	Water sprayer
	.195	.000	**.002****	.116	Ergonomic knife
innovative/conservative	.299	**.018***	**.003****	.216	Vase
	.257	.320	**.010****	.201	Water sprayer
	.357	.560	**.029***	.517	Ergonomic knife
elegant/massive	.053	.714	**.004****	1.000	Vase
	.207	**.001****	.458	.117	Water sprayer
	.000**	**.000****	**.000****	**.000****	Ergonomic knife
# below significance level of 0.05	2	6	11	5	All products

*. Significance level below or equal to 0.05

**. Significance level below or equal to 0.01

Comparing the total number of significant differences between the evaluation of the prototypes and real products, 2D images show the best approximation of reality having only two significant out of 15 possible deviations. Contrary, the AR application provide poor results with 11 significant deviations. There are no conspicuous patterns regarding the selected impressions. The number of identified, significant deviations concerning impression profiles varies merely between 4 (modern/traditional; innovative/conservative) and 6 (elegant/massive) out of a possible 12. Furthermore, there are no product-specific dependencies as there are eight significant deviations per product. Yet, it must be noted that in the VR application, the vase, whose primary stimulus is seeing, is rated close to the original, whereas the water sprayer and the ergonomic knife as more complex products with a higher degree of (physical) interaction are evaluated with much deviation.

3.3. Impact of a user's technology acceptance on subjective product evaluation

In terms of the user characteristics and the deviation of subjective quality between prototypes and real products, there is only one significant correlation connecting the deviation of the 3D print and real product with the user characteristic *'visual information processing'* (r = -.312, p = 0,004). The correlation coefficient indicates that a strong visual information processing favours a reduction of deviations (see Figure 3a). People who often imagine complex issues visually and who generally find it helpful to think in images and shapes are therefore able to evaluate 3D printed prototypes very closely to the real product.

Analysing the usage / system characteristics and the deviation of subjective quality between prototypes and real products revealed three significant correlations. Hereby, the deviation of the VR visualisation and the real product correlates with the *'perceived pleasure'* during the use of the VR application (r = .226, p = 0,028). Participants who had a lot of fun using the VR application showed greater deviations in the evaluations (see Figure 3b). It is assumed that the perceived pleasure distracts from the actual task and thus negatively influences the evaluation. The *'perceived pleasure'* is also dependent on the VR *'experience'* (r = -.395, p = 0,000), whereby the pleasure decreases with increasing experience. Accordingly, the usage and system characteristic *'experience'* could have an indirect influence on the evaluation as well. The two remaining significant correlations are found within the context of the AR application. On the one hand, the deviation of the AR visualisation and

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the real product correlates with the *'ease of use/behavioural control'* during the use of the AR application (r = -.235, p = 0,023). Participants who perceived the use of the iPad for viewing the products in AR to be difficult showed greater deviations in the evaluation than participants who found it easy to use (see Figure 3c). Difficulties in the correct use of AR may not only distract the participants from the task but can also lead to distorted presentations that could negatively influence the whole impression. On the other hand, the deviation of the AR visualisation and the real product correlates with *'experience'* (r = -.243, p = 0,020), whereby the deviation decreases with an increasing experience (see Figure 3d). Analogous to the characteristic *'ease of use/behavioural control'*, it can be assumed that experience will reduce usage errors and avoid distractions caused by the AR technology.

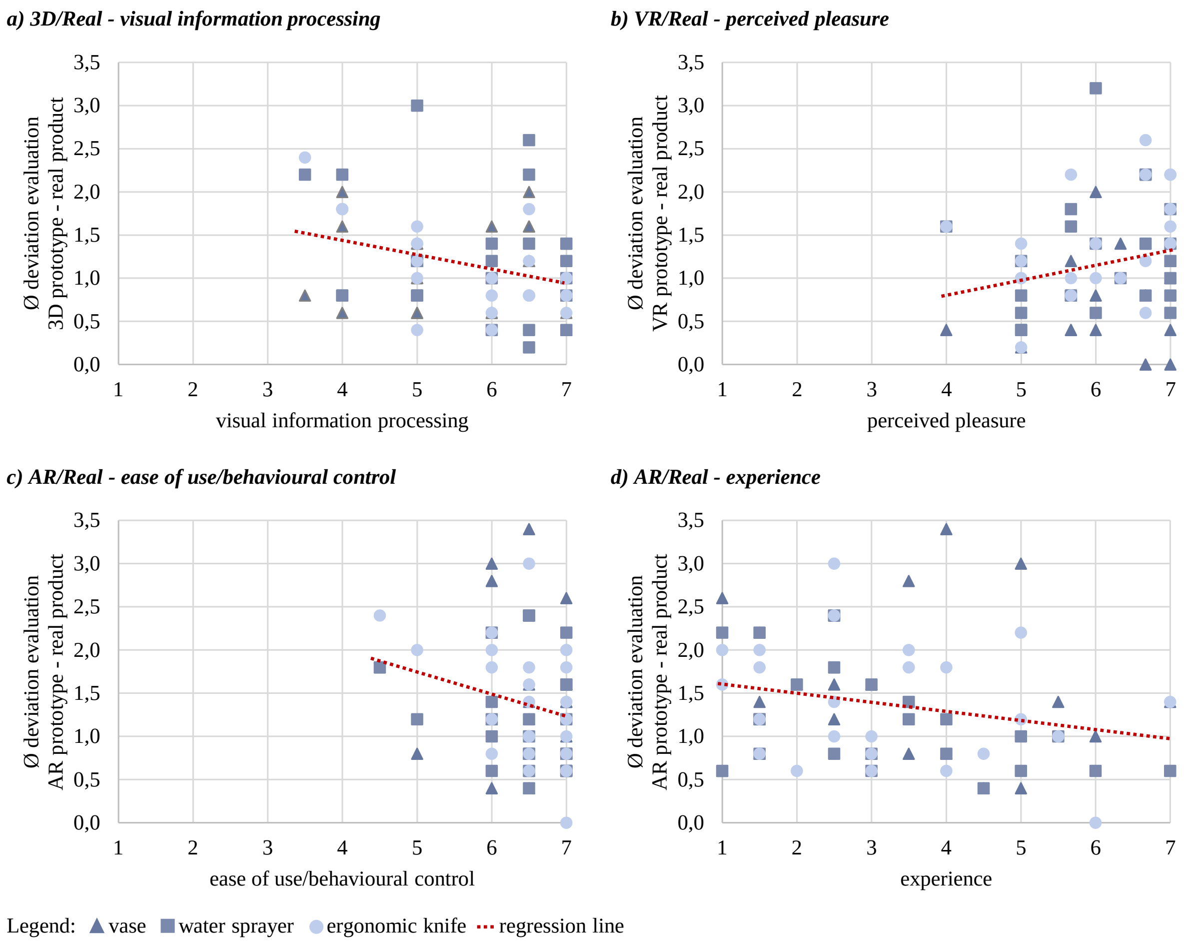

Figure 3. Scatter plots of significant correlations of deviation between AR/VR/3D prototypes and real products (y-axis) and usage/system characteristics of technology acceptance (x-axis)

3.4. Technology ranking

An overall ranking of the applied technologies was conducted in the end of the study revealing 2D images perceived as the most unpleasant (average ranking: 3.2) and 3D printed prototypes as most pleasant (average ranking: 1.9). AR and VR both hold the middle ranks with an average ranking of 2.5 (AR) and 2.4 (VR) (see Table 2). In addition, 20 out of 24 participants reported some kind of disappointment while evaluating the prototypes of the four applied technologies. Thereby, 1 participant mentioned 2D images, 4 participants mentioned 3D, 7 participants mentioned AR and the majority of participants (10) mentioned VR as most disappointing technology.

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Table 2. Ranking of the most un-/pleasant technologies

		Ranking			
		2D image	**3D print**	**AR**	**VR**
Mean value (with 1(best) - 4(worst))		*3.2*	*1.9*	*2.5*	*2.4*
Frequency per ranking	1. most pleasant	3	10	5	6
	2.	3	7	7	7
	3.	4	7	7	6
	4. most unpleasant	14	0	5	5

4. Discussion

4.1. Reflecting the research questions

RQ1: Do different forms of product (re)presentation, which is determined by the used prototyping technology, influence subjective quality evaluation of prototypes and which of them provide the most realistic image of a product's subjective quality?

Using paired t-tests, it was statistically significantly shown that the (re)presentation of prototypes causes deviations towards a realistic evaluation of subjective quality. This was the case in 24 out of 60 examined pairings of prototype evaluation and evaluation of the real product. With the fewest deviations, the 2D image clearly stands out as good basis for a realistic evaluation of subjective product quality. 3D printed prototypes as well as a visualisation of virtual models in VR also offer a reasonable benchmark showing only a few deviations. In the specific context of the conducted study, there are first implications that products that require a primarily visual product perception can be well evaluated in VR. Most deviations concerning the evaluation of the real product occurred in the AR application. Some influencing factors could already be identified through the investigation of various technology acceptance characteristics (see RQ2). In addition, from all technologies used to (re)present prototypes, the AR application was the most difficult to use. Using 2D and 3D applications, the image or the printed prototype could simply be picked up and analysed, whereas applying AR required the iPad to be held correctly and, if necessary, to rotate the prototype and reduce or enlarged it on the screen at the same time. Other AR applications (e.g. smart glasses) might provide a better ease of use but were not yet evaluated within the chosen study design. Thereby, VR as a technology also may seem more complex first, but after putting on the VR glasses with the help of the study leader, the participant was able to move freely in the virtual world.

RQ2: Does a person's technology acceptance influence the subjective quality evaluation of a prototype?

The correlation analyses conducted as part of the data analyses confirmed the statistically significant influence of some technology acceptance characteristics on the realistic evaluation of subjective product quality. Contrary to expectations, the user's acceptance characteristics have only a limited effect on the examined technologies (3D/Real - visual information processing). On the system side, there are three influences of acceptance characteristics to the technologies (VR/Real - perceived pleasure; AR/Real - ease of use/behavioural control; AR/Real - experience). Thereby, the identified connection between a simple use of AR and the enhancement of a realistic evaluation using the same technology is an important indicator for the explanation of the deviating evaluations within the study regarding the AR application.

4.2. Practical implications

From a practitioner's perspective, the added value of the study particularly lies within being able to better assess which prototyping technology provides a realistic and reliable evaluation of subjective product quality in early design phases. Despite modern and versatile technologies, based on the findings of this study, the use of 2D images illustrating spatial models is recommended. Although the participants found 2D images to be the most unpleasant compared to the other technologies, participants are still only rarely disappointed by using 2D images while they provide the most realistic results at the same time. Furthermore, there are no significant dependencies between the evaluation

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and the technology acceptance (user, usage and system). Compared to 3D printing, VR and AR, the preliminary effort required to prepare the virtual model is also the lowest. Moreover, participants can be interviewed anonymously and independent of location without having to maintain expensive technology.

4.3. Limitations

Like all empirical studies, the one conducted is subject to certain limitations. Twenty-four young and educated people participated in the study. The sample is thus small and homogeneous. The number and diversity of the participants should therefore be increased in follow-up studies. Especially the investigation of the technology acceptance of elderly could reveal interesting new findings in addition to the current group of participants. Moreover, an influence of the pandemic-related protective measures on the study results cannot be completely excluded, even if these were tolerated by all participants. Another limitation is the number of technologies and products included. Besides different products with different complexity or level of user-product interaction, there are also more prototyping technologies that should be examined. Especially in the context of early phases in product design, drafts or conceptual sketches should be included.

5. Conclusion and outlook

Gathering a realistic and valid evaluation of subjective product quality in early design phases can be achieved through the use of prototypes. However, the conducted study shows that the accuracy of the evaluation is subject to different influences. In addition to the form of (re)presentation, which is determined by the applied prototyping technology, it is also the user's acceptance (user, usage and system) of the technology that has an impact. As a reliable solution, the 2D image of spatial models is still outperforming the more complex technologies. Nevertheless, the modern applications of 3D printing, AR and VR are also achieving first realistic evaluations. Improving these technologies in terms of their potential for realistic measurement of subjective product quality seems reasonable, as these technologies are perceived more pleasant to use by the participants than the 2D image. In future research, further causes for deviation in subjective quality evaluations should therefore be explored in detail and appropriate measures for the elimination of interfering factors should be developed. Thus, the subjective quality of products can be further strengthened in the early phases of product development improving the overall user experience of products.

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