Impact of Method Users on the Application of Design Methods - Assessing the Role of Method-related Background Knowledge

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Abstract

By conducting experiments in controlled environments, design researchers test the suitability of design methods for users in practice. However, users in practice bring a variety of background knowledge that is not reflected by the samples with homogeneous knowledge used in controlled environments, especially student samples. To investigate the influence of background knowledge, two method validation experiments with participants with different background knowledge were replicated and evaluated. The results show an influence of background knowledge regarding method use and outcome. Therefore, the background knowledge of the participants must be taken into account when planning method validation experiments in order to ensure that the results are valid for practice.

Keywords

Design Methods, Design Research, Method Validation, Experimental Research

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1. Introduction

Design methods are used by design engineers in practice as support in various design activities for a wide range of different application purposes [1]. These purposes include, for example, the promotion of creativity in the case of ideation methods, or supporting the modularization of products and product families [2]. The design engineers applying these methods differ in their method-related background knowledge due to different educational and professional experiences [3], e.g., which type of methods they are used to. At the same time, method researchers continuously seek to provide design methods that are suitable for the different application purposes and method users [4]. To this end, design method validation is necessary to assess the suitability of a design method relating to its purpose for an intended group of method users, and thereby to gain insights into the application of a method for further improvements.

Following [2, p. 5], method validation is understood in this contribution as „[...] all research activities that investigate whether a design method can fulfil its purpose for an intended context." In these activities, different success criteria for the suitability of a design method are to be considered using different types of studies. Possible studies are, for example, illustrative example applications, descriptive studies, or experiments [2]. The success criteria to be considered are *applicability*, *usefulness* (comprised of *efficacy* and *effectiveness*), and *acceptance*, based on [5]. That is,

- *applicability* is understood as how well a design method can be applied by users [4, 6–8];
- *usefulness* refers to the extent to which a design method achieves its predefined goals [4], covering direct effects on a method user in controlled environments (*efficacy*) and indirect effects on performance (*effectiveness*) [9];
- and *acceptance* refers to the method user's attitude toward and willingness to use a design method, and is among others influenced by perceived *usefulness and applicability* [10, 11].

These success criteria for method validation are independent of the chosen type of study. To ensure the suitability of design methods before they are deployed in practice, validation experiments in a controlled environment are well suited [12]. By excluding the influence of disturbing variables, causal relationships between the application of methods and effects on users can be derived without risking to fail in practice. Considering the criterion of *usefulness*, the criterion of *effectiveness* does not apply because indirect effects cannot be captured in experiments. Hence, method validation involves different types of studies for evaluating the validation success criteria, whereas method validation experiments in controlled environments require the criteria *applicability*, *acceptance*, and *efficacy* to be assessed.

These method validation experiments do not match the conditions of design practice. According to [13], this concerns external validity. External validity captures the extent to which the results of experiments can be generalized [13]. That is, in the context of method validation experiments, the transferability of the results to the context of practice. One aspect of this is population validity, i.e. the suitability of the selected sample of the experiment [13]. In the context of method validation experiments, this describes the extent to which the sample of the experiment represents the designers for whom the method was developed. If one wants to increase the generalizability of the findings of an experiment, replication studies are appropriate [13]. These test the reliability of findings in other contexts. Internal validity, by contrast, refers to whether changes in the dependent variable are due solely to the independent variable [13]. Consequently, in method validation experiments, the extent to which the selected conditions of the experiment, such as the selected sample, reflect design practice influences external validity with regards to the application of the method in practice.

Since students offer the advantage of a high internal validity compared to practitioners [14], as well as availability at universities, they are often chosen as sample for design method validation experiments in controlled environments. As these students usually attend a similar academic program with similar lectures at the same university, they share a homogeneous background knowledge on the application of methods due to their similar education. Thus, students differ from design engineers with regard to population validity due to the difference in the characteristic of background knowledge, as design engineers do not share similar background knowledge. As a result, design method validation experiments with student samples carry the risk of reducing population validity due to the unrepresented knowledge difference, affecting external validity, and therefore the transferability of the findings to design practice.

The influence of knowledge on engineering design has already been shown in several studies. For example, [15] have shown the influence of knowledge on how a design task is approached; [16, 17] have shown the influence on the need to use a design method; and [7, 18] have shown the influence on the appropriateness of a given design task. Therefore, transferring these findings to the context of method validation, there are indications that the background knowledge of the participants influences the results of method validation experiments and thus the external validity. As such, [19, 20] highlight the relevance of pre-checking and balancing the technical understanding and the methodological skill set of study participants in method validation. Hence, the problem is that the influence of method-related background knowledge on method validation experiments is unknown in the state of research, which prevents evaluation of the external validity.

1.1. Contribution of this Article

To solve the stated problem, this article investigates the influence of method-related background knowledge for future consideration in the assessment of the external validity of method validation experiments. This influence manifests itself in the relationship between the background knowledge and the success criteria *applicability*, *acceptance*, and *efficacy*. Therefore, the research question of this contribution is: *Does the background knowledge of method users influence the applicability, acceptance, and efficacy of design methods in experimental validation?* The answer to this question will provide insights into the influence and lead to recommendations for researchers to conduct method validation experiments.

2. Research Approach

To answer the research question, the success criteria had to be assessed experimentally for groups of participants with varying background knowledge. Therefore, two method validation experiments were replicated mutually at two universities, the Hamburg University of Technology (TUHH) and Karlsruhe Institute of Technology (KIT). The results of the two replicated experiments were subsequently compared with the two initial experiments, which were conducted at the respectively opposite university. The initial experiments provided the reference values for the success criteria, with the two replicated experiments complementing each other: *Replication study I* assessed *acceptance* and took *applicability* into consideration, while *replication study II* assessed *efficacy* for another design method. Mutual replication resulted in samples with different background knowledge, while the different emphases of method education at the two universities were preserved across replication. In the end, the insights gained in both replication studies were merged to answer the research question and deduce recommendations for researchers.

Replication of previously conducted method validation experiments with participants with different background knowledge was a practical way to answer the research question, as it allowed the comparison of two data sets with regard to the research question without the effort to collect them both. At the same time, by assessing the success criteria through experiments with more than one design method, it was possible to prove the transferability of the findings to other design methods. Hence, by replicating previous method validation experiments on multiple design methods with participants with differing background knowledge, the results could be analyzed toward the influence of background knowledge on *applicability*, *acceptance*, and *efficacy*.

3. Replication Study I

The first study to be replicated was conducted with the objective of qualitatively validating the *acceptance* of a discursive approach, i.e. a teamwork-based method for designing visualizations as product development tools [21, 22]; hereafter referred to as *design method I*. Among others, its *applicability* and perceived *usefulness* and by this also *acceptance* were measured in contrast to an intuitive approach, i.e. brainstorming; hereafter referred to as *alternative method*. For the evaluation of the replication study, a comparison to the initial study which was conducted at TUHH was necessary. Therefore, both studies are briefly summarized with a focus on the replication and the change in the participants' background knowledge.

In accordance with the experiment design, previous knowledge of visualization, modularization, and teamwork were defined as relevant for the design method's application. In the initial study at TUHH, which was conducted with 38 participants, the experiment was integrated into the context of the "Advanced Product Development" lecture, in which both the basics of modularization and various comparable methods are covered. Therefore, some background knowledge of modularization could be assumed to be given. Likewise, the participants had already gained experience with teamwork due to their previous education. A pre-test showed slightly diverse background knowledge of visualizations. Hence, all fields of knowledge were assessed and homogeneous groups were formed accordingly.

3.1. Participants in the Replication

19 students participated in the replication at KIT, whereby 9 students left the experiment prematurely, which left us with data from 10 students (more details in 3.3). *Replication study I* was part of the course „Mechatronic Systems and Products", which is part of the bachelor in mechatronics at KIT. Prior to the study, the participants had not heard of *design method I* or its application example, the visualization of the impact model on modular product structures [23]. Due to their previous university education at KIT, it could be assumed that the students had no previous knowledge of modularization. With regard to teamwork, however, they had already been able to gain extensive experience due to their previous education. Pre-tests on the background knowledge of visualizations could not be conducted, therefore open questions asking for background knowledge were included in the questionnaires.

3.2. Investigation Setup and Procedure

The design of the study was accomplished using the Design Method Validation System [24]. The participants were divided into control and experimental groups and were given the task to design new visualization concepts for the impact model on modular product structures as published in [23]. As *design method I* is defined as a teamwork-based method, the task was carried out in groups of about 4-5 participants. To enable the participants to carry out the task within the limited workshop time, all groups were given the method phases 1 to 3 of [22] in advance, leaving the experimental groups to carry out phase 4. Herein, visualization techniques and principles [22] suitable for the task should be extracted from design catalogues and morphological boxes should be built out of these. New alternative visualization concepts should be achieved by the end of phase 4. In the control groups, participants went from method phase 3 directly to brainstorming, i.e. the intuitive approach, from where they were in turn supposed to create visualization concepts. Thereby the groups only differed in their approach to finding new visualization concepts; the experimental groups continuing with the discursive *design method I*, while the control groups were given an intuitive *alternative*. The way of approaching a new visualization concept was thus the independent variable and *acceptance* the dependent variable.

In contrast to the experiment at TUHH, the replication was part of a lecture without compulsory attendance, making it impossible to pre-assess students' background knowledge. Consequently, groups were randomly assigned. For data collection, three methods were used based on previous experience [25]: a questionnaire, observations, and interviews. The questionnaire utilized a 4-point Likert scale and an avoidance answer option to measure participants' attitudes toward ease of use, usefulness, and quality of their concepts. Free text fields were included to capture opinions and hints. Observations were documented in writing and photos by trained observers. Interviews allowed participants to express opinions more freely, providing mainly qualitative data for evaluating *acceptance*. Additionally, the combined results of the likert-scaled questionnaire were used as a simplified measure through mean values, assessed using the Mann-Whitney-U test. The significance level $p = 0.05$ was chosen.

3.3. Results & Evaluation of the Influence of the Background Knowledge

19 participants appeared at the beginning of *replication study I*, who were then divided into two control groups (C) and two experimental groups (E). In the course of the experiment, nine participants left. At the end, two participants of experimental group E1, three out of five participants of the control group C1 and all five participants of the second control group C2 remained. Experimental group E2 left the event completely, meaning that not the full data range is available on this group, but rather the observations.

The two remaining participants of E1 reported that they were initially overwhelmed with the abundance of information presented in the design catalogues for visualization principles and techniques and spent some time just looking through the material. Eventually, they deviated from the exact method instructions and loosely followed the method given. For E2, the observations showed that they indeed worked with the material before leaving the experiment. In between, however, there was also an exchange with C2. During this exchange, one participant in the experimental group commented on the perceived higher ease of use of the *alternative method* group C2 was using for their solution finding.

Both control groups followed the instructions of the *alternative method* in a concentrated manner. They faced minor challenges working together and some difficulties in understanding the initial concepts that needed optimization. The desire for a more structured approach was expressed in a few cases.

All groups that completed the study produced convincing visualization concepts. Participants in *replication study I* confirmed in free-text answers having limited prior experience with visualizations but lacked knowledge of modularization. The main difference between the replication at KIT and initial study at TUHH was the participants' background knowledge of modularization, evident from fewer questions in the replication about the impact model of modular product structures. There were isolated questions about the representation itself, whereas in the initial study there were also questions about the consistency of the impact model presented in the task description. The difference in the number of participants between the studies might explain this observation. Comparing the results of the *acceptance* score that can be extracted from the sum of the questions of the likert-scaled questionnaire, neither for the initial nor for the replication study significant values were obtained for the differences in the control and experimental groups (see Table 1). However, if both study results are combined, a significant difference in the *acceptance* tendencies can be identified with a weak effect (according to [26]), exact Mann-Whitney U test: $U = 2.000$, $p = 0.009$, $r = 0.289$.

Table 1: Comparison of the combined acceptance scores of the initial study, replication study and both combined.

Study	Experimental Group	Control Group	Mann-Whitney *U* Test
Initial	Design Method I 5 groups	Alternative Method 4 groups	n = 38 U = 2.000 p = 0.063 r = -
Replication	Design Method I 1 group	Alternative Method 2 groups	n = 10 U = 0.000 p = 0.667 r = -
Both combined	Design Method I 6 groups	Alternative Method 6 groups	n = 48 U = 2.000 p = 0.009 r = 0.289

From the questionnaire results we conclude that the intuitive method of brainstorming achieved better *acceptance* scores among the participants than the structured and discursive *design method I* according to [22]. Although some participants expressed a desire for a structured approach, users of *design method I* in turn reported difficulties in handling the information provided. This was more evident in the replication, where the participants had less background knowledge of the task. Here, the example from the task was described as challenging in interviews and free-text answers. It can therefore be deduced that design method *acceptance* in experiments depends on background knowledge of the participants in the form that, (1) the less related procedural knowledge they have, the more likely they are overwhelmed by discursive approaches, and that (2) the less task-related theoretical knowledge they have about the problem to be tackled by the method, the less likely they perceive the *usefulness* of performing a discursive approach. Both forms of background knowledge must be taken into account when planning an experiment.

As a limitation, it has to be mentioned that despite having rich data from the 3-fold data collection, due to reduced participant numbers in *replication study I*, the significance of the study results in total is limited.

4. Replication Study II

The second study to be replicated was a study by [27] with the objective of quantitatively validating the *efficacy* of the qualitative modeling method based on the Contact and Channel Approach (*design method II*). *Design method II* has the purpose of supporting the generation of specific design artifact knowledge [28].

In the replicated study by [27], two runs of the experiment were conducted at KIT. For the purpose of this paper, we will limit ourselves to the first run, since a more distinct difference in background knowledge was assumed. In this initial experiment, 159 students in the first semester of a chemical and process engineering course were used as a sample in the context of a mechanical design course at KIT. The students had already heard about the method prior to the study, but were not trained in its use. The individual working practices of *design method II* and basic principles of qualitative modeling that underpin the method were cornerstones of the colloquium and were taught from the beginning. Hence, due to the features of the first semester students, a generally low background knowledge could be assumed in the initial study with an advantage toward *design method II* arising from the colloquium.

4.1. Participants in the Replication

Replication study II was conducted with 29 students in the master's lecture „Advanced Product Development" at TUHH. Prior to the study, the participants had not heard of *design method II*. Neither were basic principles of qualitative model building part of the course. The participants therefore only had a general background, which resulted from their previous bachelor degree, without any relation to the method. Therefore, compared to the participants of the initial study, it could be assumed that they had a more extensive general background, but no background knowledge related to *design method II*.

4.2. Investigation Setup and Procedure

The *efficacy* of the method was concluded by the performance of the participants in solving knowledge-intensive tasks. The following is an overview of the procedure and tasks used in the initial experiment in [27]. For more details, e.g., in terms of operationalization, see [27].

During the experiment, the participants passed the following steps: Solving control group tasks using a first technical system, receiving a training course on *design method II*, and solving test group tasks using a second technical system. This procedure allowed two measurements per participant to be recorded, even though a lasting effect was expected from being taught *design method II*. In order to exclude a learning effect due to the order of the technical systems, the participants were divided into two groups (A & B) at the beginning of the experiment, which differed only in terms of the order of the technical systems. The technical systems used were a snap fit joint and a cartridge press. [27]

The control and test group tasks are comprised of two complementing tasks: (1) a web-based design task, and (2) the evaluation of the behavior of system variants. The tasks were designed as follows: (1) In task 1, the participants received a design variant of a technical system in a web-based CAD configurator. This variant included four function-restricting faults. The participants had to identify the function-restricting faults and resolve them by changing the relevant design parameters in the configurator. They received one point for each resolved function-restricting fault. This resulted in a metrically scaled variable ranging from 0 to 4. (2) In task 2, the evaluation task, the participants received six different system variants of one of the technical systems successively and had to predict the overall behavior. Through all system variants, the same four overall behaviors were available for selection. For each correctly assigned system behavior, the participants received on point, resulting in a metrically scaled variable ranging from 0 to 6. The two tasks thereby complemented each other by requiring different levels of knowledge. While the design task addressed the assessment of the impact of individual design parameters, the evaluation task addressed the assessment of the overall behavior of the systems. As both tasks resulted in metrically scaled variables, differences due to the groups could be assessed with the Mann-Whitney *U* test and the *efficacy* was evaluated using the Wilcoxon test. The significance level $p = 0.05$ was chosen. [27]

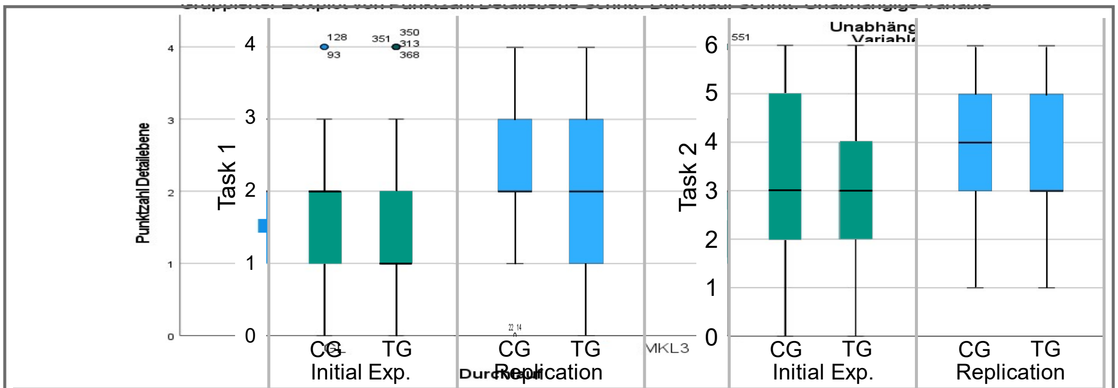
4.3. Results & Evaluation of the Influence of the Background Knowledge

Figure 1 presents the results of *replication study II* in blue, with the scores in the tasks across the considered task and group. The *efficacy* of *design method II* corresponds to the difference between the control and test group in each task, captured by the effect value (r).

In task 1, group A ($Mdn = 2$) showed no significant difference in the scores overall compared to group B ($Mdn = 2$), exact Mann-Whitney *U* test: $U = 395.5$, $p = 0.838$. Accordingly, no significant difference arose from the group assignment. The assessment of the *efficacy* of *design method II* in task 1 showed that the participants achieved a significantly higher score in the control group ($Mdn = 3$) than in the test group (Mdn =3; Wilcoxon signed-rank test; $z = -2.004$, $p = 0.045$, $n = 29$). According to [26], this was a medium effect ($r = 0.372$). Consequently, *design method II* showed a negative *efficacy* in task 1.

In task 2, group A ($Mdn = 3.5$) showed no significant difference in the scores overall compared to group B ($Mdn = 4$), exact Mann-Whitney U test: $U = 429.0$, $p = 0.736$. Accordingly, no significant difference arose from the group assignment. The assessment of the *efficacy* of *design method II* in task 2 showed no significant difference between the control group (Mdn = 4) and the test group (Mdn = 3; Wilcoxon signed-rank test: $z = -0.255$, $p = 0.798$, $n = 29$). Consequently, *design method II* showed no *efficacy* in task 2.

For a conclusion on the influence of the background knowledge on the *efficacy* measured in a method validation experiment, the results of the replication have to be compared with the initial experiment of [27]. For this reason, Figure 1 shows the results of the initial experiment supplementary in green. Differences in *efficacy* can be seen by comparing the effect values (r) within tasks between the experiments. Task 1 reveals that the scores in general were influenced as the broader background knowledge of the master's students led to higher scores in general. Further, the *efficacy* was influenced as well, the scores of the participants with less related and broader background knowledge (i.e. in the replication) decreased as a result of using the method, indicating a negative *efficacy*. Such a decrease was not measured in the initial experiment. In task 2, the scores in general were influenced as visible by the quartiles with the participants in the replication achieving higher scores. The *efficacy*, though, was not influenced. The implication is that a difference in the background knowledge of the method users may, but does not always, influence the *efficacy* measured in a validation experiment.



Results for efficacy	Task 1 Initial Exp.	Task 1 Replication	Task 2 Initial Exp.	Task 2 Replication
n	71	29	111	29
z	-1.516	-2.004	-1.144	-0.255
p	0.129	0.045	0.253	0.798
r	-	0.372	-	-

Legend: CG = Control group; TG = Test group; Statistical test used: Wilcoxon signed-rank test

Figure 1: Comparison of the *efficacy* (difference between control and test group) of the design method between the initial (green) and the replication (blue) experiment separated by the two tasks.

5. Discussion

The confirmation of the influence of the method users' background knowledge on the success criteria is consistent with the assumptions based on previous findings from the state of research as stated in the introduction, underlining its relevance for external validity. As such, in agreement with [19, 20], we find that the participants' *acceptance* scores as well as the handling of and attitude toward the methods, and thus also the *applicability* of the methods, are influenced by their background knowledge. Further, the influence on *efficacy* supports that the users' knowledge influences the design outcomes, as observed in the results of the knowledge-intensive tasks used in *replication study II*. From this perspective, the conclusions of previous method validation experiments should be limited in their transferability based on the descriptions of the sample, and comparisons between these experiments challenged.

However, the state of research also results in possible limitations of the results of the replications. As such, the differences between the samples of the studies conducted may have influenced the approach to the tasks as per [15], possibly overlapping with the influence between background knowledge and method application. The findings of *replication study I* support this assumption, as the participants were potentially overwhelmed due to a lack of background knowledge, and thereby affected in their approach. Further, the suitability of the design tasks toward the samples may have been different as per [7, 18]. This assumption is supported by the different levels of values among the studies on *design method II* as seen in Figure 1. Whether the difference in suitability also interferes with the *applicability, efficacy, and acceptance* of the method can't be derived from the replication studies. Consequently, the findings of the replication studies reflect the state of research, while interferences arising from the context of replication have not been examined.

6. Conclusion and Outlook

The replications demonstrate that the background knowledge of the sample influences the results of design method validation experiments and thus, if neglected, the external validity toward practice. Design researchers must take this into account during method validation to ensure that method users with different background knowledge can benefit from a method and that they are provided with suitable methods. From the results, the following recommendations can be derived for the consideration of background knowledge in method validation experiments: (1) define the procedural and task-related theoretical background knowledge necessary for the successful method implementation and application; (2) assess the participants' existing background knowledge before carrying out the experiment; (3) if necessary, adapt the experiment to the background knowledge, e.g. by giving more detailed guidance on how to apply the design method, or by providing additional task-related theoretical knowledge; and (4) conduct an experiment with a sample with different background knowledge to support the external validity of the findings obtained with homogenized samples.

Still, there is a need for further investigation of the influence of background knowledge. In this context, the discussion indicates the need to investigate interfering influencing variables, such as the suitability of the task, to specify the findings. Furthermore, the extent of the influence of background knowledge on the success criteria is still unknown, in particular with respect to different emphases in the background knowledge. Here, further experiments in which further disturbing factors are excluded can provide more detailed insights.

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