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Design and evaluation of digital tools to expand experience in vocational education

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Abstract

Vocational education and training (VET) is the most popular form of upper-secondary education in Switzerland, with more than two-thirds of the teenagers enrolling in a VET program after finishing their compulsory education. The vast majority of the Swiss VET systems have a dual-track structure where students learn in schools for one or two days per week while they do an apprenticeship in a company for the remaining days. Their professional competencies are developed through a combination of workplace experiences reinforced by the theoretical knowledge learned in school.

While the apprenticeship at workplaces provides valuable experience to the learners, one concern is that there is a lack of diversity in the experiences of an individual apprentice. Motivated by this limited experience of VET learners in the workplace, the goal of our research has been to explore the possibilities of expanding their experiences. Focusing on design-related professions in VET, we consider exploring digital variations of a design as a way to expand the original experience related to the design. The research objectives of this thesis are (1) exploring possibilities to expand the experience of learners in design-related VET and (2) investigating the potential benefits of the expanded experience. To accomplish the research objectives, we formalize the idea of expanding experience for VET learners by defining the three dimensions of expansion: parametric, temporal, and social. We explore these three dimensions in three studies.

For the parametric dimension, we investigate how learners explore a multidimensional space of possible designs using a digital tool and how we can support the process with an interface that enables disentangled exploration of design parameters. We present a tool called BloomGraph that has been developed for florist apprentices to explore flower bouquet designs, and the results from an experimental study that investigates the effectiveness of a graph interface for design exploration.

For the temporal dimension, we explore how we can support the VET learners with envisioning the designs that change over time. We present a virtual-reality tool called GardenVR developed for gardener apprentices that allows creating a garden and exploring it in an immersive environment. In an experimental study with gardener apprentices, we investigate how they explore the time dimension using the tool, compare the tool with the current method of practice, paper-sketching, and study how the two interfaces can be combined in an instructional design to enhance the design outcome.

Lastly, for the social dimension, we present a tool called Mixplorer that has been designed for a classroom scenario of gardener apprentices. The tool provides a way to socially explore design spaces by allowing the apprentices to create an initial design and recombine it with the designs of other learners. We present the results of two studies conducted using the tool that investigate its feasibility in the VET setting, potential benefits for the learners, and the effectiveness of the design-mixing process in creative practices.

Key words: Vocational education and training, Design learning, Learning technologies, Virtual reality, Design space exploration, Creativity support

Résumé

La formation professionnelle (FP) est la forme la plus populaire de l'enseignement secondaire supérieur en Suisse, avec plus de deux tiers des adolescents suivant cette voie après avoir terminé leur scolarité obligatoire. La grande majorité des systèmes de formation professionnelle suisses ont une structure à deux axes : les élèves apprennent à l'école un ou deux jours par semaine et effectuent un apprentissage en entreprise les autres jours. Leurs compétences professionnelles sont ainsi développées par les expériences sur leur lieu de travail et sont renforcées par les connaissances théoriques acquises à l'école.

Si l'apprentissage sur le lieu de travail apporte une expérience précieuse aux apprenants, le manque de diversité dans les situations rencontrées est une source de préoccupation. Motivés par ces limitations pour certains apprentis, l'objectif de notre recherche a été d'explorer les possibilités d'élargir leurs expériences. En nous concentrant sur les professions liées au domaine de la conception, nous considérons l'exploration de variations numériques d'une certaine conception comme un moyen d'élargir l'expérience originale de création. Les objectifs de recherche de cette thèse sont (1) d'explorer les possibilités de diversifier l'expérience des apprentis lors de la formations professionnelles dans les domaines liés à la conception et (2) d'étudier les avantages potentiels de ces expériences élargies. Pour atteindre ces objectifs, nous formalisons l'idée d'étendre l'expérience des apprenants en FP en définissant les trois dimensions de l'élargissement : paramétrique, temporelle et sociale. Nous explorons ces trois dimensions dans trois études.

Pour la dimension paramétrique, nous étudions d'abord comment les apprenants explorent un espace pluridimensionnel de conceptions possibles à l'aide d'un outil numérique. Ensuite, nous analysons comment nous pouvons soutenir le processus avec une interface qui permet une exploration dissociée des différents paramètres de conception. Nous présentons un outil appelé BloomGraph, développé pour les apprentis fleuristes afin d'explorer les conceptions de bouquets de fleurs, ainsi que les résultats d'une étude expérimentale qui examine l'efficacité d'une interface graphique pour l'exploration des différentes conceptions possibles.

Pour la dimension temporelle, nous étudions comment nous pouvons aider les apprenants d'une formation professionnelle à envisager des conceptions qui évoluent dans le temps. Nous présentons un outil de réalité virtuelle appelé GardenVR, développé pour les apprentis jardiniers, qui permet de créer un jardin et de l'explorer dans un environnement immersif.

Dans une étude expérimentale avec ces apprentis, nous examinons comment ils explorent la dimension temporelle à l'aide de l'outil, comparons l'outil avec la méthode actuelle de pratique, l'esquisse sur papier.

Enfin, pour la dimension sociale, nous présentons un outil appelé Mixplorer qui a été conçu pour un scénario de classe d'apprentis jardiniers. L'outil fournit un moyen d'explorer socialement les espaces de conception en permettant aux apprentis de créer une conception initiale et de la recombiner avec les conceptions d'autres apprenants. Nous présentons les résultats de deux études menées à l'aide de l'outil, qui examinent sa faisabilité dans le cadre de la formation professionnelle, les avantages potentiels pour les apprenants et l'efficacité du processus de mélange de conceptions dans les pratiques créatives.

Mots clefs : Formation professionnels, Apprentissage du design, Technologies d'apprentissage, Réalité virtuelle, Exploration de l'espace de design, Soutien à la créativité.

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1 Introduction

1.1 Motivation

Vocational education and training (VET) is the most popular form of upper-secondary education in Switzerland, with more than two-thirds of the teenagers enrolling in a VET program after finishing their compulsory education [118]. The vast majority of the Swiss VET systems have a dual-track structure where students learn in schools for one or two days per week while they do an apprenticeship in a company for the remaining days. Their professional competencies are developed through a combination of workplace experiences reinforced by the theoretical knowledge learned in school. The idea behind the dual-track system is based on the concept of learning through experience and it is theoretically grounded on Kolb's theory of experiential learning [63]. In dual-track VET systems, concrete experiences are acquired in the workplace and reflection on those experiences happens in the school.

While the apprenticeship at workplaces provides valuable experience to the learners, one concern is that there is a lack of diversity in the experiences of an individual apprentice [57]. This limitation of experiences is introduced by multiple factors including the type, style, and size of the workplace. First, some companies are specialized in very specific tasks within the profession and they do not cover the whole spectrum of the activities related to the profession. Second, companies in design-related fields often establish their own style of design and the experience as an apprentice is biased towards the style of the company. Finally, the size of a company can affect the scope and the diversity of the experience of its apprentices. For example, a florist apprentice working at a small flower shop in an airport can be repeatedly making bouquets of the same design for a welcoming purpose and it is unlikely that they will have much experience on wedding or funeral bouquets during the apprenticeship. In addition to these factors, the tasks given to the apprentices tend to be distant from the ones they will have to perform further down their career path. As an apprentice, they may do the daily care of flowers, but not get a chance to do the original designs.

Motivated by the limited experience of VET learners in the workplace, the goal of our research has been to explore the possibilities of *expanding* their experiences. Focusing on design-related professions in VET, we consider exploring digital variations of a design as a way to expand the original experience related to the design. Exposure to design variations is an important part of learning in most design-related activities. It can help the learners acquire a better understanding of the design space which plays an important role in finding solutions to a creative task [25, 66, 67]. As an inexperienced designer, they are often unaware of the full extent of the design space and it is difficult for them to understand how their design is just one of many possible solutions to the problem that they are trying to solve. In this thesis, we are interested in supporting VET learners with exploring design spaces using tools that can provide digital variations of an original design. This is the way we look at the expansion of experience throughout this thesis.

1.2 Research objectives

The main objectives of this thesis are summarised as follows:

- **Exploring possibilities to expand the experience of learners in design-related VET**: The idea of expanding experience using digital technologies is novel in the VET context and it is the goal of this thesis to explore this new territory. We focus on design-related professions in VET systems and propose three dimensions of expansion, with all of them starting from real-world experiences. For these three dimensions we present three applications that we implemented. These applications are designed for specific target groups and they show how the concept of expanding experience can be applied in realistic scenarios of VET learning. The applications are tested with the VET learners in order to validate their designs.
- **Investigating the potential benefits of the expanded experience**: Using the applications implemented, we show the effects of the expanded experience on the VET learners through three experimental studies. Each study is designed to gain insights into the potential benefits of the expanded experience in different domains. As it is a new territory to be explored, we try to gain a broad understanding over different aspects rather than focusing on a single factor. Our interests include learner behavior using the application, effect of the expanded experience on the quality of design outcome, comparison with conventional method of practice, and creativity support of the application.

To accomplish the research objectives, we formalize the idea of expanding experience for VET learners by defining the three dimensions of expansion: parametric, temporal, and social. Expansion along the parametric dimension is done through an algorithm that can generate variations of a design by changing the values of design parameters. We propose a tool that allows a structured exploration of the design space by systematically changing the properties of a design (i.e., changing a particular property of the design such as color, texture, or shape). Expansion along the temporal dimension is achieved with a tool that computes and visualizes how a design would change over time. It helps learners experience something that is difficult or impossible to do in the real world: traveling in time. And the expansion along the social dimension refers to exploring the design space using the designs of other people as guides. Prior work tells us that seeing the designs created by others is already meaningful in terms of supporting creative thinking and improving design quality, but we take one more step to generate and explore new designs by recombining the designs of multiple learners.

1.3 Thesis roadmap

In the next chapter (**Chapter 2**), we provide the background and the research context. We explain the Swiss VET system and its dual-track approach, and discuss the previous efforts on supporting the VET learners using digital technologies. We also discuss the workplace experience of VET apprentices and how it can be limited by different factors. In **Chapter 3**, we present the three dimensions of expansion that we propose. We explain how the three dimensions were chosen for the VET context. And we provide examples of expanding experience along the three dimensions.

Chapters 4, 5, and 6 present three experimental studies we conducted. As mentioned above, the studies explore the three dimensions of expansion. Each study focuses on one of the dimensions and explores different ways to expand the experience along the dimension. In each chapter, we present an application that has been implemented to demonstrate expanding experience in a concrete scenario, and also present the results of an experiment conducted using the application to validate the design and investigate the impact on learning.

In **Chapter 4**, we explore the parametric dimension of expansion. We present an online application that can support florist apprentices with the design space exploration of flower bouquets. Starting from an initial design, the tool can generate systematic variations of it and provides learners with a graph-based interface that enables structured exploration of the design space. We present an experimental study that we conducted with florist apprentices in the Swiss VET system. The main question we ask in the study is whether the VET apprentices can mentally construct multidimensional abstract space and navigate through it. We specifically investigate (1) the effect of the graph-based interface on their understanding of the space and (2) the strategies adopted by them in the graph exploration. Our results show that the graph interface can foster more efficient navigation towards a goal design but with longer exploration of each intermediate design. And the participants with more strategic behavior on the graph exploration acquired a better understanding of the design space.

In **Chapter 5**, we present our study for the temporal dimension. We explore the domain of garden design as the temporal aspect is important in their work but difficult to observe in the real-world experience. We present an immersive virtual reality (VR) application for garden design and exploration where learners can explore a garden by controlling the time variable. In an experimental study, we compare the VR interface for designing with conventional paper interface in terms of the quality of design outcome. Furthermore, we investigate how the two interfaces can be combined together in an instructional design to maximize the learning outcome. From the results, we find that the two interfaces have distinct advantages in terms of different aspects of the design quality and the order between the two can have a significant effect on the final design outcome.

In **Chapter 6**, we explore the social dimension. For the social expansion of experience, we present an application with a novel mechanism that allows designers to take an initial design and mix it with the designs of others. The application has been developed for gardener apprentices to explore garden designs. Using the application, learners can explore an ill-defined design space through "social design space exploration." We present an interview study that we conducted with garden-design instructors and a controlled experiment with novice designers using the application. Our results show that the social exploration activity has a potential benefit for VET learners in terms of divergent thinking and that the design-mixing function can support their creativity and help produce more novel designs after using it.

Finally in **Chapter 7**, we summarize the main findings of this thesis, address their implications, and discuss the limitations and future research directions.

2 Research context

2.1 Swiss vocational education and training system

When it comes to vocational education and training (VET), Switzerland is one of the top countries in the world with a reputation of excellence. The Swiss VET system offers professional training in approximately 240 different occupations and it is often praised as one of the factors that explain the low unemployment rate and the health of the small and medium enterprises (SMEs) in the country [115]. The VET system provides a pathway to upward mobility in Switzerland, and many of the nation's most influential and successful people are graduates of the VET system. These are just some of the reasons that VET is so popular among the Swiss youth. In Switzerland, students choose between the two types of upper-secondary education after finishing the compulsory education: an academic track that leads to higher education and a VET track with 3–4 years of apprenticeship. In 2019, nearly 70% of the students chose the VET track as their upper-secondary education and this proportion has remained constant for years [118]. Based on the high social acceptance of VET, most companies offer apprenticeships to the students and the number of offers of apprenticeship contracts is usually higher than the number of demand in many situations.

The VET system of Switzerland also provides numerous forms of support for the job mobility of trained professionals. Upon successful completion of a VET program, students receive a federal diploma and are considered to be qualified professionals in the field. These diplomas are recognized nationwide and allow regional mobility within the country. The system also supports mobility within professions. It offers flexible structures with different pathways to handle the transition when students want to change their profession after a year or two.

There are also possibilities to continue with further education after the upper-secondary level VET. Apprentices in a 3–4 year VET program for the Federal VET diploma have the option of preparing for the Federal Vocational Baccalaureate (FVB) [118]. Those who pass the FVB examination may enrol in a Swiss university of applied sciences (UAS) and pursue a Bachelor's degree. Moreover, with the FVB, one can prepare for the University Aptitude Test (UAT), which opens a way for enrolment in a cantonal university or federal institute of technology.

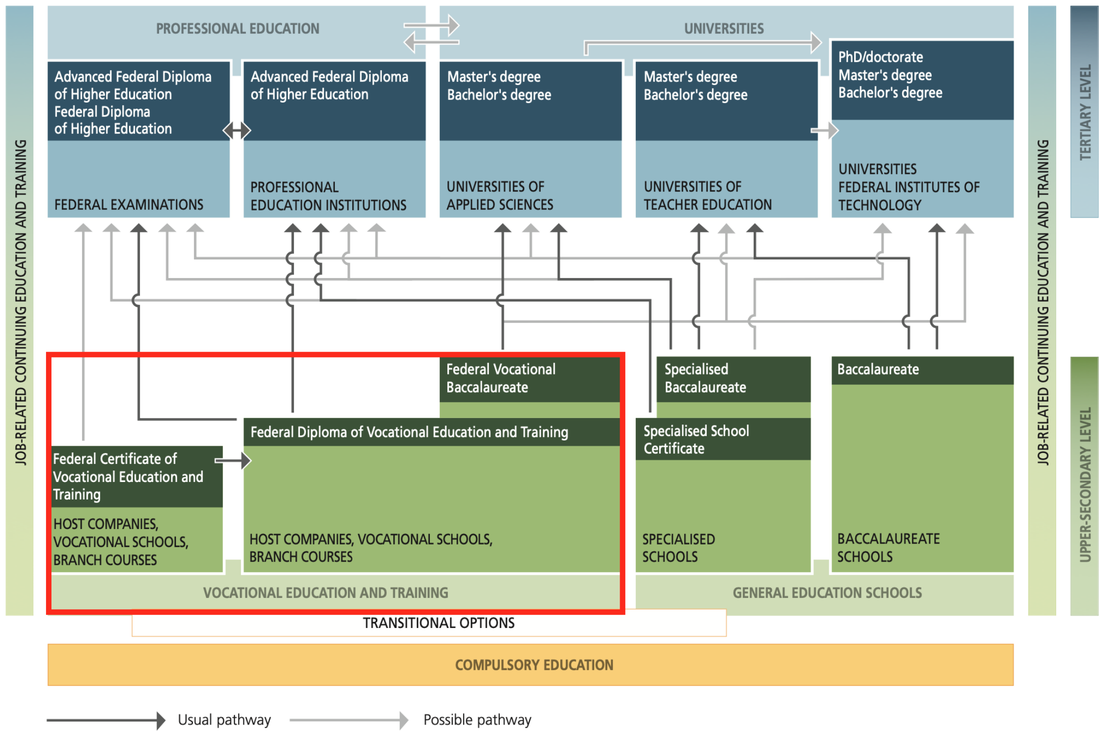

Figure 2.1 – Possible pathways in the Swiss educational system. The red rectangle shows the upper-secondary level VET part of the system. This figure is taken from SERI [118]

These options make the Swiss VET system flexible enough for the learners to continue with higher education further down in their careers or even switch between the vocational and the general education path. Figure 2.1 shows the Swiss educational system including the possible pathways related to VET.

One of the characteristics that describe the Swiss VET system is its dual-track approach. A dual-track VET system combines part-time learning in schools with part-time apprenticeship in companies. More than 90% of the VET programs in Switzerland are of the dual-track structure. The remaining 10% have a single-track structure that only involves school learning. In a dual-track system, students usually spend one or two days per week in school while they do an apprenticeship in their host companies for the remaining days. From the school side, they learn theoretical knowledge specific to the profession as well as general subjects (e.g., language, mathematics, and history). On the company side, they have hands-on experiences in authentic situations so that they acquire practical skills and knowledge. Students develop professional competencies through first acquiring practical experiences in authentic environments of workplaces followed by reinforcing with theoretical knowledge from schools.

2.2 Leading house Dual-T

Despite the strength and the solidity of the Swiss VET system, one of the issues in the dual VET system is that the knowledge learned from the two learning contexts often remains encapsulated in its original context [98]. Different contexts of learning in VET often have separate aims, content, and sociological organization [39] and consequently, apprentices often perceive the gap between the two learning locations [121]. The knowledge acquired in school is predominantly explicit and theoretical, whereas the workplace knowledge is mostly implicit and tacit, often contextualized in a specific situation [29, 77]. The difference between the two learning contexts is not undesirable—it is actually what makes the dual system strong in terms of providing diverse experience to the learners. What is necessary is the support for connecting and integrating the skills and knowledge acquired from the two.

Leading house Dual-T was a research project funded by the State Secretariat for Education, Research and Innovation (SERI) of Switzerland which aimed to bridge the gaps between different learning contexts of Dual VET systems. The main hypothesis of the project was that digital technologies have the potential to connect workplace experiences and classroom learning. This hypothesis was translated into a pedagogical model called 'Erfahrraum' for designing educational technologies for dual VET systems [107]. The term Erfahhraum is a portmanteau consisting of the two German words, 'Erfahrung (reflected experience)' and 'raum (room).' The Erfahrraum model facilitates creating 'Erfahrungen' through the processes of experiential learning and reflection. It proposes the design of shared digital spaces for reflecting on the experiences acquired in different learning contexts in which VET takes place. It does not refer to a specific technology for digital learning, but rather a framework for designing a digital activity that allows bridging the gap that exists between different learning contexts. And the activity in the digital space should allow learners to reflect on their real-world experiences by capturing and augmenting them. Figure 2.2 shows the Erfahrraum model.

Based on the Erfahrraum model, researchers have designed digital activities that can foster reflecting on experiences in dual VET systems. One way that has been explored is through the use of online learning journals. Cattaneo et al. [11] have studied the use of online learning journals for apprentice chefs to capture workplace experiences and share them in school classrooms. They reported positive results in terms of effectiveness in school learning and satisfaction. In a similar study, Mauroux et al. [82] showed that promoting reflective writing in the learning journals had a positive effect on the metacognitive learning strategies as well as the performance on the final exams. There are studies that involved other forms of digital artefacts such as augmenting video recordings from workplaces for chefs and car mechanics [84], tabletop activity that allows simulating warehouse layout for logisticians [20], and augmented reality application for carpenters that lets you apply loads and visualize forces on physical structures [77]. These studies validate the Erfahrraum model by demonstrating positive effects on VET learners in terms of their motivation as well as academic performance.

The research presented in this thesis is part of the Dual-T project and it shares the main

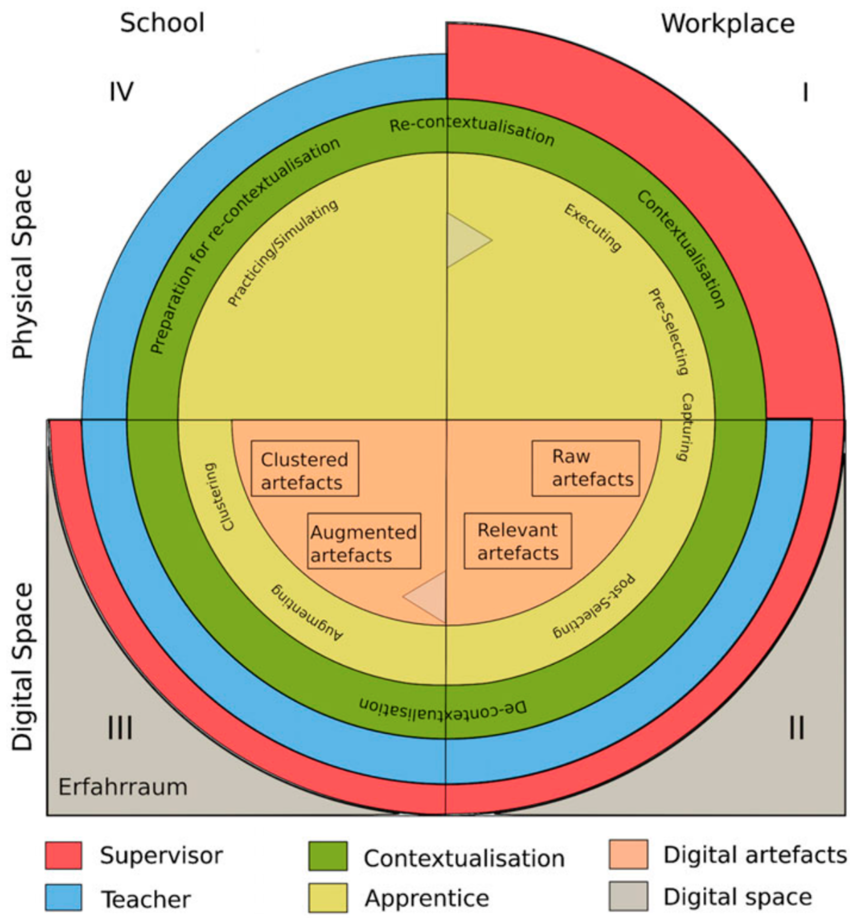

Figure 2.2 – The Erfahrraum model: a pedagogical model to inform the design of technology-enhanced VET learning activities. This figure is taken from Schwendimann et al. [107]

research focus with the previous work described above. The focus of the previous work was primarily concerned with connecting workplace experience to school activities in accordance with the Erfahrraum model. The Erfahrraum model also serves as the foundation for the research presented in this thesis, but what differentiates our work from the previous effort is that our focus is on the experience side of the flow. We investigate the design of digital activities that can enrich and expand the workplace experiences (this corresponds to the quadrants II and III of the model).

2.3 Experience as a VET apprentice

Practical experiences acquired in the workplace are the main source of learning in the dual-track VET system. Apprentices typically spend four days a week in their workplace, and the practical knowledge acquired here is complemented by learning which occurs in the schools, where they reinforce and connect this practical knowledge with theories. This model is grounded on Kolb's theory of experiential learning [63].

Experiential learning is defined as "creating knowledge through the transformation of experience" by Kolb [63]. He places particular emphasis on the importance of hands-on experiences. Ideally, these experiences should happen at the start of the learning process, since learning is a holistic process that builds upon and connects real-world experiences [48]. Through authentic practice-based learning, students' experiences can lead to self-efficacy which, in turn, results in increased confidence in handling specific tasks [91].

The combination of experiential learning with VET makes sense since the theory of experiential learning promotes providing means for the students to build knowledge and skills from direct experiences [91]. Kolb describes experiential learning as a cyclic process of four stages: concrete experience, reflective observation, abstract conceptualization, and active experimentation [63]. The initial step of concrete experience involves placing learners into problematic situations while encouraging them to be open-minded [91]. The workplace experience in the dual VET system implements this first step well. The second and third steps of reflection and conceptualization are better suited for school learning, where apprentices can connect their workplace experiences with theoretical knowledge. The final stage, active experimentation, can happen once the apprentices have returned to the workplace. They return back to the problematic situation, but they are encouraged to experiment with their newly-connected knowledge acquired in steps two and three. The cyclic process of the experiential learning theory is closely related to the cycle of the Erfahrraum model—the Erfahrraum model proposes a flow of acquiring and capturing experience, reflecting on it, and practicing. Kolb's experiential learning theory is viewed as a way to fill the gap between explicit and tacit knowledge [47] and the Erfahrraum model suggests a method to implement this theory in a manner that is tailored to the dual-track VET system.

As experience plays the central role in achieving the learning outcomes of experiential learning, one of the factors that determines the quality and content of what is learned is the richness of experiences [46, 125]. When the experience is limited, it can result in limited overall learning as experiential learning is dependent upon the quality of experience [31]. The experiential learning process can be viewed as an interplay between exploitation and exploration in terms of the acquisition of experience [46]. While both of them are critical for the learning outcome, exploration is concerned with creating variety in experience, and thrives on experimentation and free associations. The variety of experiences can be improved through search, discovery, novelty, innovation, and experimentation and it can enrich the resources of learning for experiential learning [46].

Despite its importance, the variety of workplace experiences can differ dramatically among apprentices. Even in a single classroom in a VET school, most of the apprentices do their apprenticeships in different host companies and their experiences are quite different from one another. There are multiple factors, often related to the characteristics of the workplace, that constrain the variety of the experience as an apprentice in VET.

One of the factors is the type of the workplace. Some companies may specialize in particular tasks within the profession, and as a result apprentices working in these companies may get limited exposure to other aspects of their profession's activities. For example, a carpenter apprentice working in a small company which specializes in computer numerical control (CNC) machines may not gain experience with other wood cutting machines. This is a general weakness of the VET system: the richness of the apprentice's experience can be limited by the professional spectrum of the company.

Another constraining factor is the style of the workplace. Especially for design-related professions such as florists or fashion designers, companies often establish their own styles for products and the experiences of an apprentice are biased towards them. These stylistic constraints make it difficult for an apprentice to experience or experiment with the designs that lie outside of the boundary of the company's style.

A third factor that can constrain the apprentice's experiences is the size of the workplace. Larger companies usually have a broader spectrum of professional activities, but as apprentices, it is likely that they are only asked to do small tasks within this spectrum. Some larger companies offer an opportunity for their apprentices to work in multiple teams during the apprenticeship in order to let them experience different aspects, but not all the apprentices have this privilege. Smaller companies often ask apprentices to do multiple tasks and the apprentices can experience various aspects of the professional work. However, related to the first factor we mentioned above, smaller companies are likely to focus on a narrow spectrum of the professional activities and the apprentices' experiences are limited by the spectrum.

In addition to these factors related to the characteristics of the workplaces, another factor that can affect the variety of experiences is the role of an apprentice in the workplace. The tasks given to apprentices are usually distant from the ones they will have to perform further down their career path. For example, an apprentice working in a warehouse is usually asked to do simple tasks such as transporting or arranging pallets, but is unlikely to redesign the arrangement of storage shelves of the warehouse to optimize the efficiency. Apprentices might learn the concept of warehouse optimization in schools, but it is not trivial for them to connect it to their workplaces as they do not usually experience it as an apprentice.

These issues are well known by stakeholders in the Swiss VET system, and there have been some efforts to address the issue of limited experience from the workplaces. The primary way that has been adopted is to provide intercompany courses to the apprentices. Once or twice a year during their training, all of the apprentices in the same profession gather to participate in special courses organized by professional associations. These courses help the apprentices gain experience on special topics of the profession (e.g., funeral bouquet making for florist apprentices or training on a special wood cutting machine for carpenter apprentices). However, there are limitations to this approach. For example, the relative infrequency of these courses has been criticized and the introduction of these courses is not always well-received by other stakeholders in the system [137, 5].

The research presented in this thesis was also motivated by the problem of limited experience within the Swiss VET system. We hypothesized that digital technologies could be used as a means to expand the limited workplace experiences of apprentices. The potential of using digital technologies for the experiential learning approach has been discussed in previous research and different combinations of the types of digital technologies and the educational settings have been investigated in recent studies [45, 60, 94]. Our work focuses on the integration of digital technologies into the experience-oriented learning environment of VET and explores the design of digital tools that can support learners with enriching their experiences.

2.4 Supporting design-related professions

There are more than 200 distinct professions within the Swiss VET system. In this thesis, we have chosen to focus specifically on design-related professions in order to explore different ways to enrich the experience with digital technologies. Approximately 10% of the professions available in the Swiss VET system belong to this group [115]. Some examples are clothing designers, interactive media designers, fabric designers, hairdressers, wood sculptors, glass painters, and of course, florists and gardeners. We decided to work with this specific target group because their workplace experiences often produce a physical artifact (e.g., a dress, a garden, or a bouquet) or physical change in a situation (e.g., a haircut). These experiences can be easily captured and transformed into a digital artefact, if they do not already take a digital form. A digital artefact that represents an experience is a key component of the Erfahrraum model. And since our goal is to use digital technologies to expand the workplace experiences of apprentices, it is necessary that these experiences can be represented in digital form so they can be ingested and transformed by the systems we have developed.

This thesis investigates how design space exploration using digital variations might provide a means to expand experience. For design-related professions, the idea of expanding experience is closely related to the idea of design-space exploration. Particularly in terms of improving the variety of experience for VET learners, digital exposure to a broader design space is certainly a way to enrich and expand their limited real-world experiences. Moreover, the importance of exploring and understanding design spaces for creative practices is already emphasized in previous research and there is already a rich tradition of supporting design-space exploration for the learners in design-related fields [109]. However, these tools tend to be designed for more academic design disciplines and there is little work done in the field of VET. This thesis aims to fill this gap by developing and evaluating digital tools to support the expansion of experience through design-space exploration.

3 Expanding experience through exploring design variations

In this chapter, we elaborate on the idea of expanding experience using digital variations of designs in VET. We also introduce the three dimensions along which experiences can be expanded. We explain how we chose these dimensions to explore and give examples for what each dimension means.

3.1 Expanding experience in design-related VET

As discussed in the previous chapter, it is not uncommon for apprentices in VET to have limited experiences in the workplace, and it is in the best interest of the VET system to find ways of supporting them by expanding their experiences, particularly for design-related professions. As an apprentice in a design-related field, the richness of experiences is directly related to the variety of designs that they get exposed to. However, if the workplace experiences are limited in scope, there is little that an apprentice can do to increase the number of designs that they see.

The idea we propose in this thesis is to provide digital variations of designs for apprentices to explore. The starting point for this process is a design taken from the apprentices' real-world experience. A potentially infinite variety of digital variations of this design can be created for the apprentice to explore. In digital spaces, one can explore as many designs as are desired. This is what we mean by expanding experience through exploring digital variations of designs. As shown in Figure 3.1, an experience of making a rose bouquet in the real world can be expanded to exploring multiple digital variations of it.

Consideration of multiple design variations is an important part of the creative process. From previous research, we know that these alternatives provide designers with a more complete understanding of the design space [42, 35] and comparing alternatives can help them make stronger critiques and better design decisions [123, 26, 67]. Exposure to these alternatives can also help overcome design fixation, which is defined as a blind adherence to a set of ideas of concepts limiting the output of design [50]. It can also improve other factors in

Figure 3.1 – Demonstration of expanding experience through exploring digital variations. A florist apprentice makes a rose bouquet (in the center) in the workplace. Her real-world experience might end there, but it can be expanded to exploring multiple variations of it in a digital space.

design processes including the quality of design outcome and support collaboration [72, 114]. However, exploring alternatives in a design space is not a trivial task, and is particularly challenging for apprentices who are novice designers. Expert designers are more capable of generating alternative designs based on their domain knowledge and previous experience [70, 133]. On the other hand, apprentice designers, without the expertise and the level of experience required for this process, stand to benefit more from technological support for design space exploration. This is the gap that our research aims to fill with the idea of expanding experience with design variations.

The act of designing can be viewed as a continuous process of searching for a solution in a space [43] and designers explore the space through a series of transformations originating in the initial state and culminating in the goal state in the space [119]. A digital tool can support this process by providing design variations that encourage designers to move out of the space of routine designs and explore the space of innovative designs. Routine designs are defined as those that proceed with a well-defined state space of potential designs that are familiar to the designer, whereas innovative designs are nonroutine designs that are outside of normal space and they have unfamiliar values of design variables for the designer [36]. Figure 3.2 shows schematic representations of the space of routine designs and innovative designs. For the VET apprentices, we theorize that the space of routine designs is shaped by

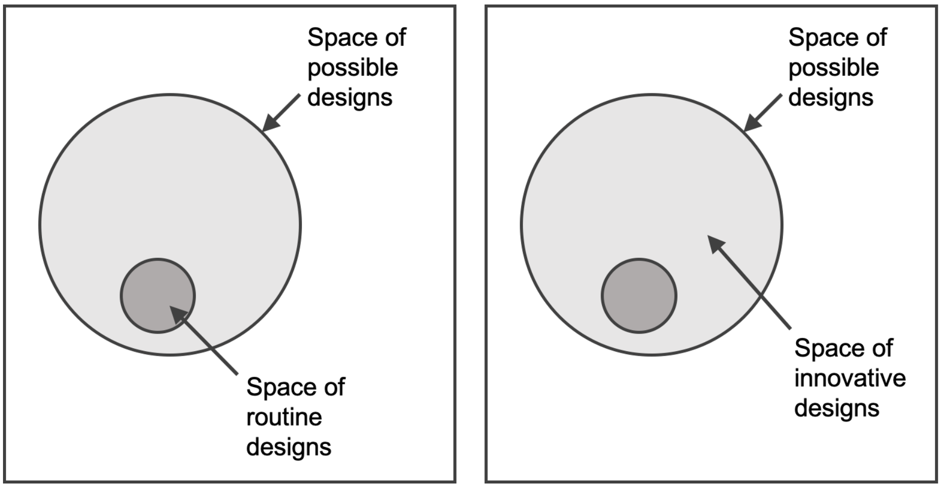

Figure 3.2 – Space of routine designs (*left*) and innovative designs (*right*). The figure is originally from Gero [36] and redrawn to improve the quality.

their workplace experiences, and that digital tools can help apprentices travel outside the boundary of workplace experiences and explore an expanded space.

Exposure to designs that are outside of the space of apprentices' routine designs is important, however, it is often not enough to simply provide these designs to them. The nature of design problems is often ill-defined and unstructured [13, 38] and exploring these types of problem spaces can be daunting. From the literature, we know that there are both positive and negative effects of being exposed to other designs and these mixed results can be due to the support that is provided around the use of them [59]. In other words, scaffolds may need to be provided to guide the integration of the resource into the learning process [28, 64, 102]. Figure 3.3 shows the process of solution search in an unstructured problem space and how scaffolding can constrain the area to be searched and guide designers in their exploration.

The three dimensions of expansion we describe below are different ways to scaffold the exploration design variations provided by digital tools. We start with a design related to a real-world experience, and then aim to support learners in exploring the digital variations generated by the tools. Our goal is not necessarily to guide learners so that they can take the most efficient path to a goal design in the exploration, but rather to let them explore a broader space as we want them to expand the experience. Therefore, scaffolding is not to constrain the exploration for efficiency (e.g., minimizing the time taken or the number of intermediate designs to find a desired solution), but to provide a structured way to explore a larger space so that the apprentices can build a map while exploring the space.

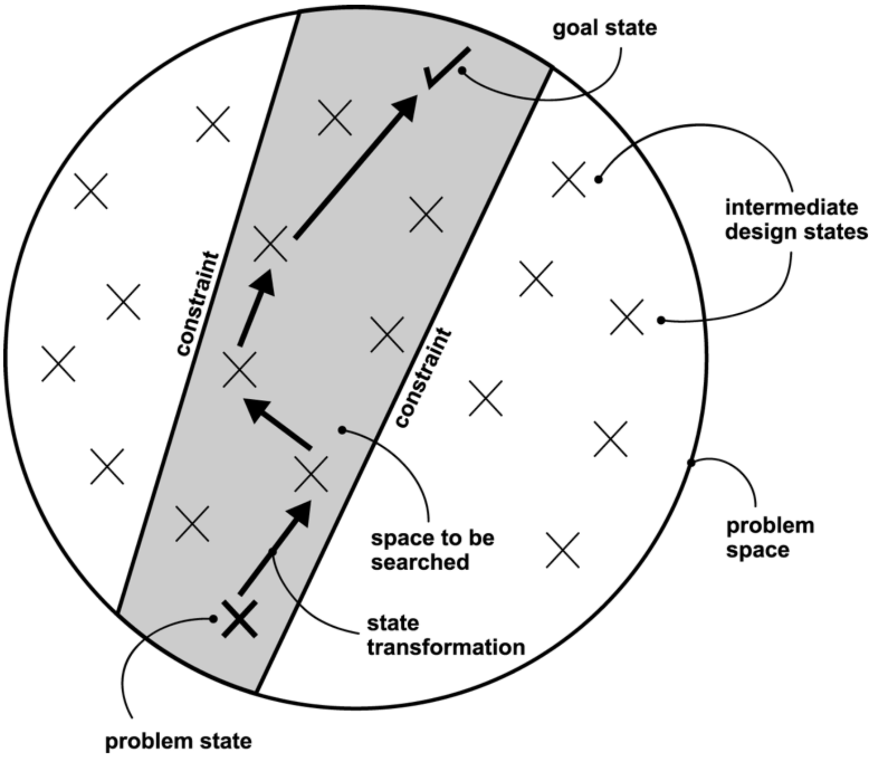

Figure 3.3 – The process of solution search in design tasks. The act of designing is a series of transformations originating in the initial state and culminating in the goal state in the space. Constraints can be introduced by scaffolding this exploration. This figure is taken from Hay et al. [43].

3.2 Three dimensions of expansion

In this thesis, we explore three different dimensions of expanding experience through the digital exploration of design variations. It is not our goal to propose an overarching framework that includes all modes of VET experience. It would be very difficult, if not impossible, to capture the full variety of workplace experiences with three dimensions unless we were to stay at an abstract level.

The dimensions of expansion we present here are three among many possible directions along which a VET experience can be expanded. The three dimensions we chose to explore emerged from real-world problems encountered by apprentices in their training. After multiple discussions with the stakeholders in a number of design-related VET, we have chosen these axes based on a set of criteria:

- A dimension of expansion should be meaningful for a target profession.

- It should be related to some difficulties that apprentices face during their learning.
- It should be in line with current teaching practices and it can be well-integrated into the VET curricula.

We explain below how we chose the dimensions, motivations behind them, and examples of expanding experience along them.

3.2.1 Parametric dimension

One question that arose from the discussions with VET teachers was about the apprentices' ability to understand a design space for creative practices and navigate it. We realized that apprentices typically lack understanding of the full design space. Simply providing them with a multitude of examples is not effective because apprentices struggle with the process of integrating the examples into a mental framework organized according to differences in meaningful design parameters. While it is common in the field of cognitive science to consider design as an exploration of the combinatorial space of independent design parameters, it might not be the case for apprentices. They might not be able to mentally construct multi-dimensional abstract space or feel comfortable to navigate through it as they are often very much concerned by the concrete shapes of their craft [87]. In order to investigate whether and how the apprentices can navigate a design space, we have explored the parametric dimension.

To give an example, imagine a florist apprentice who made a flower bouquet in the workplace. She had to rush to finish making it because the customer was waiting and she did not have enough time to think about other possible designs she could have made. After work, she launches a digital tool to explore other bouquet designs. Starting from the design she made during the day, she starts changing different design parameters of the bouquet to see what it would look like. She explores many different combinations of these parameter values that she did not think of, and by doing this, she sees how changing the value of each design parameter would have transformed the bouquet.

Expansion along the parametric dimension involves providing apprentices with a tool that can generate systematic variations of a design and enable structured exploration of the design space. New design variations can be generated by iteratively changing the value of a specific design parameter. Figure 3.4 illustrates how a real-world experience might be expanded by exploring digital variations in the parametric dimension. The goal is to help the apprentices understand that a design is a consequence of the choices of independent design parameters, and to provide them with a way to navigate the multidimensional space of these parameters.

In Chapter 4, we explore the parametric dimension in an experimental study with florist apprentices. We investigate how they navigate a space of bouquet designs and what their strategies are for the exploration, and we analyze the effect of structured exploration of the space in terms of their understanding of the space.

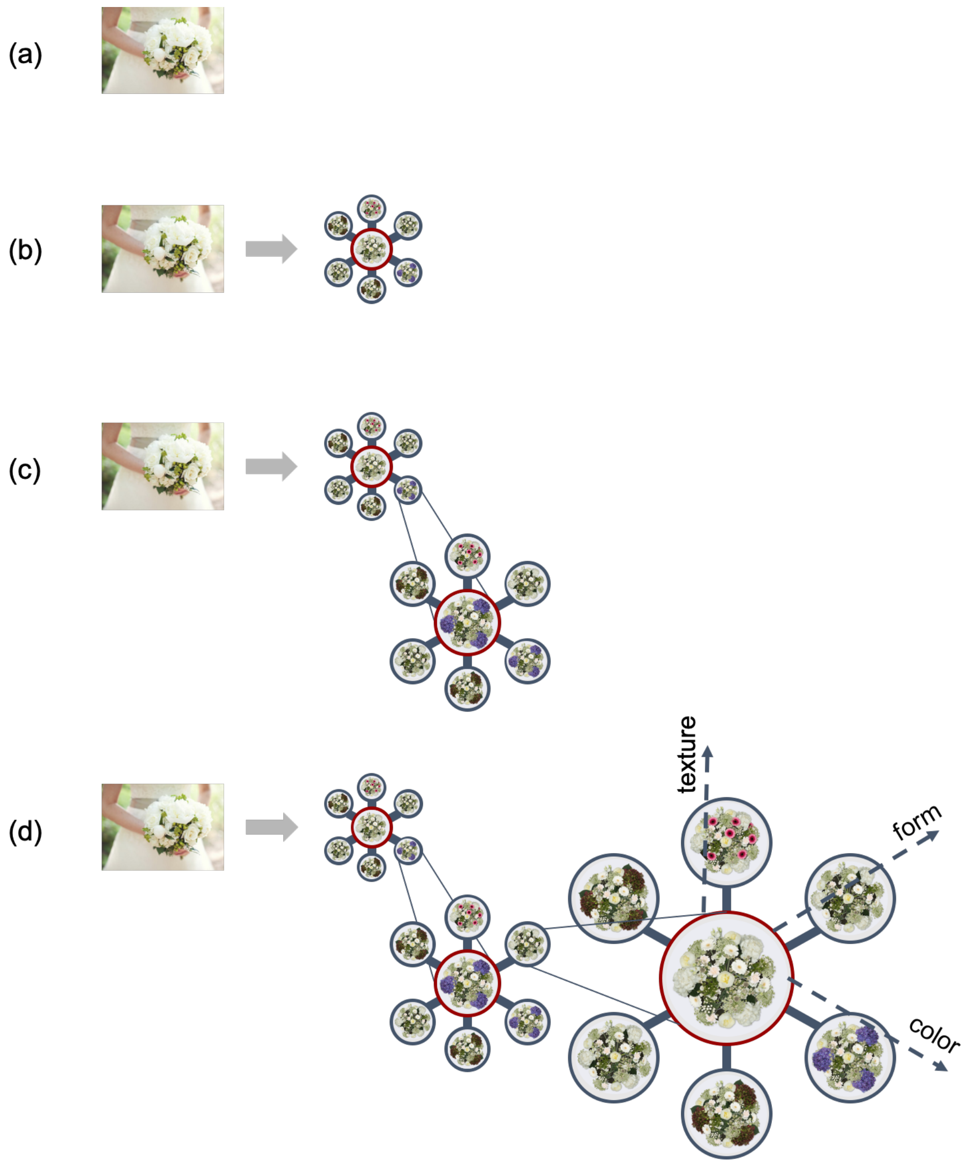

Figure 3.4 – An example of parametric expansion of experience for florist apprentices: (a) Starting with a design from a real-world experience, and (b-d) navigating the design space by selecting a digital variation of a design repeatedly.

3.2.2 Temporal dimension

For some professions such as gardeners, florists, or landscape designers, their designs change over time as the elements of their designs (e.g., trees or plants) grow and transform. Sometimes, these temporal changes are undesirable, such as when the roots of a tree destroy a sidewalk or driveway, and it is often too late or costly to undo a mistake by the time one finds out that it has occurred. For this reason, the designers should create a design not only for the present time, but also for the future. While professional designers have accumulated enough experience to envision the future, this is rarely the case for apprentice designers. They could benefit from having a tool that can support them with visualizing and experiencing how their design would change in time. This is the motivation for exploring design variations in the temporal dimension.

Imagine a gardener apprentice who is working on the garden of a church. He thinks that a maple tree would be great for the garden, but he is not sure where to plant it exactly. He wishes that he could try planting it in different places to see how it looks, but he knows it is not possible. Furthermore, he is especially concerned about the shade it will create in different seasons, and also how it will appear after it grows for a few years. He has to solely depend on his imagination, but due to his lack of experience he lacks the imaginative abilities of an expert. This is precisely the type of problem that can be solved by providing digital tools that support the expansion of experience in the temporal dimension.

Expanding experience along the temporal dimension allows apprentices to experience the future of their designs. Time is a critical dimension for many design-related professions, but as demonstrated in this example, it is often difficult to experiment in the real world. One of the advantages of digital environments is that we can simulate things that are difficult to do in real life. Using a digital tool, it is possible to travel in time and simulate how a design would change.

In Chapter 5, we explore the temporal dimension with gardener apprentices. We present a tool using immersive VR technology that can simulate time change in different scales and allows the apprentices to experience the garden in an immersive environment, and we investigate the benefit of the tool compared to traditional paper-sketch interface in terms of the quality of design outcome.

3.2.3 Social dimension

In a typical classroom of a VET school, apprentices often work for different companies for their apprenticeships and therefore, they have very different workplace experiences. As mentioned in previous chapters, the workplace experience of an individual apprentice can be limited and may only cover a small portion of the professional activities. Since the workplace experience is the main source of learning in VET, these apprentices end up getting exposed to a small area within the larger design space. Even though an individual apprentice's space can be limited, collectively the apprentices in a classroom can make a more broader coverage of the space. By sharing their designs with peer apprentices, the apprentices can work together to explore a broader design space. This is how we conceptualize exploration in the social dimension.

Expanding experience in the social dimensions involves sharing designs among multiple apprentices. What we propose is not only sharing the designs, but also a way to generate new designs through a process of recombination. The process of selecting candidate designs and mixing them to produce new ones scaffolds the process of design exploration using multiple apprentices' designs, and it fits well with the classroom setting of dual-track VET schools.

For example, imagine a classroom of gardener apprentices who are working on an activity of designing a garden for their school. One of the apprentices is doing an apprenticeship in a company that specializes in building stone pathways. Another apprentice works for a company that specializes in making flower beds. Each of these apprentices creates a garden design for the activity. Using a digital tool, they can generate new designs by recombining components of their original designs, and compare them to find the best design.

We explore the social dimension in Chapter 6. We investigate how this novel mechanism of design exploration would be incorporated into the teaching of garden design, and we also investigate the effect of the design-mixing process on creativity support as well as design outcome.

4 Parametric expansion: BloomGraph

In this chapter, we explore the expansion in the parametric dimension. As introduced in the previous chapter, expanding experience in the parametric dimension can be done by providing a digital tool that generates systematic variations of a design and enables a structured way of navigating the design space. The goal of the tool is to help the learners explore other possible designs that they might not have considered while providing a support for navigating the multidimensional space of design parameters. We introduce a bouquet design exploration tool we developed for florist apprentices and present the results of an experimental study.

This chapter corresponds to the following publication:

Kim, K. G., Oertel, C., & Dillenbourg, P. (2021). How florist apprentices explore bouquet designs: Supporting design space exploration for vocational students. *International Journal for Research in Vocational Education and Training (IJRVET)*, 8(1), 65–86 [59].

4.1 Introduction

Exposure to design variations is an important part of learning in most design-related vocations. It could help the learners in acquiring a better understanding of the design space which can play an important role in finding solutions to a design task [25, 66, 67, 123]. Without exploration, they often interpret the design problem too narrowly and choose a solution to the problem too early without discovering potentially meaningful directions in the design space [56, 19].

Exploration of design variations is not a trivial task in a real-world situation. For instance, it is very difficult for a florist apprentice to explore a broad design space with real flowers, which would take an impractical amount of time and resources. The atmosphere of the workplace, where they have to deal with real customers, often makes it even more difficult for them. It is likely that they choose a bouquet design after only considering a limited set of variations without having the opportunity to explore other possible designs. Experienced florists have the experience and they are capable of visualizing the design space in their heads, but this is not the case for the apprentices. It is probably difficult for them to understand how a design is one of many possible solutions to the problem in a large space. This is the gap we aim to bridge with a digital tool we introduce in this chapter.

We have chosen florist as the target profession and investigated how we could design a tool to support them with parametric expansion of their experience. In order to allow florist apprentices to explore variations of a design, we implemented a web application called "BloomGraph." BloomGraph provides a graph-based interface to navigate through flower bouquet designs. The key concept behind the design of BloomGraph is the axes of transformation—each axis of the graph leads to transforming a particular attribute of the design and, therefore, learners can systematically navigate the design space. We hypothesize the positive effect of the disentanglement of design parameters on understanding of the design space.

This chapter demonstrates how a digital tool can be designed in order to enable VET learners to explore design variations in the parametric dimension and how they can benefit from this additional experience. The experimental study presented in this chapter shows how the learning outcome is affected by a graph-based interface for exploration and the exploration strategy adopted by the learners.

4.2 Related Work

The benefits of design examples and variations in creative practices have been demonstrated in many studies. Exposure to design alternatives provides awareness of the design space of potential options [66]. Additional value is provided through the design process as people recognize and compare the alternatives [123]. When comparing designs, learners are focused on the common relational structure, aiding abstraction of the underlying schema [37]. The potential benefit of multiple examples on the understanding the design space is the core idea supporting our work presented in this chapter and it is tested in the experimental study.

While having examples can provide some benefits in a design task, there are mixed results to their effect in terms of design outcome. One negative effect is the conformity toward examples. The studies by Marsh et al. [80] and Smith et al. [113] show that design outcomes are likely to contain features of the examples after getting exposed to multiple examples. However, the negative effect of examples is debatable as there are also many positive results in the literature. Exposure to multiple designs can reduce fixation in a design task [50] and early and repeated exposure to examples improves creativity in design [67].

These mixed results may be due to the support that is provided around the use of examples. During the learning process, it is often not enough to just provide a resource to learners but scaffolds may need to be provided to guide the integration of the resource into the learning process [28, 64, 102]. In the case of examples, it is important to investigate how people explore the given examples and what is the effect of the exploration. Without exploration, people often interpret the frame of the design problem too narrowly [56] and may choose a design concept too early without identifying a valuable direction [19]. In terms of the exploration strategies, Ball et al. [8] compare novices and experts on how they make use of examples in design analysis. In their study, experts show more schema-driven use of examples (i.e., the recognition-primed application of abstract experiential knowledge) than case-driven (i.e., invocation of concrete prior design problem with a similar solution), with respect to novices. Najar et al. [85] show that the students with higher levels of knowledge pay more attention to the schema of the data than the weaker students. Our interest lies in the same domain as these studies. In this chapter, we investigate how people explore a given set of designs while focusing on the effect on their understanding of the structure of the given design space.

As the way one explores design examples has an effect in a design task, some studies have investigated how to support the design exploration. Lee et al. [72] propose an interactive example gallery for a web design task. Their study shows that structured corpus navigation can help users find inspirational examples and facilitate design. Ritchie et al. [101] show that a systematic design exploration tool can help users finding relevant and inspiring design examples. Their tool allows users to explore the examples ordered according to the styles. Our study also proposes a design exploration tool for a design task, but what differentiates it from the previous work is that it allows learners to explore the design space by actively selecting which parameters to vary. We use the design variations that are systematically generated based on the current design as the source of exploring the design space.

4.3 Research Questions

The findings from previous research have triggered the questions for our experimental study: Given a digital tool that provides variations of bouquet designs, how would florist apprentices explore the space? We investigate how they explore a set of variations focusing on the effect on their understanding of the structure of the given dataset. Specifically, we address three research questions in order to achieve the goal:

- RQ1: What is the effect of the graph interface on the design exploration in terms of their understanding of the design space?
- RQ2: What are the strategic behaviors of the learners in the graph exploration?
- RQ3: Can we predict the behavior of the learners in the graph exploration using their gaze data?

The first question investigates the effectiveness of providing a structured interface for the learners to navigate design spaces. We hypothesize that the disentanglement of the design parameters provided by the interface can foster acquiring a better understanding of the design space. The second and the third questions focus on the behavior of the learners in using the graph interface. By answering these questions, we explore the strategies used when exploring the designs using the interface and how the gaze data in particular can be used to better understand their behavior.

4.4 BloomGraph

For this study, we have developed a web application called BloomGraph that can support florist apprentices with bouquet design exploration [57]. The interface of the BloomGraph application is shown in Figure 4.1. As seen on the left side, the navigation graph consists of the center node that shows the current bouquet design and four proposed variations around it. The proposed design in each axis is a variation of the current bouquet in terms of a specific design parameter: color, form, texture and spacing. These parameters were chosen after discussions with florist teachers to align with the concepts of bouquet designs that they were teaching. When a user selects one of the variations, it comes to the center and a set of new variations of that design are proposed. Above the graph, there is a history bar that shows all the designs the user went through. Using the history bar, a user can backtrack to previous designs. On the right side, there is an interactive 3D viewer. The current bouquet design is shown in 3D and the user can rotate or zoom in/out. In the viewer, the user can also see the names of flowers by hovering the mouse pointer over them.

BloomGraph allows users to explore the design space as they follow the nodes in a graph. In the graph, each axis leads to a different variation of the current design. By clicking the nodes in different axes, users can vary the design systematically in terms of the important design parameters, thus providing a structured way of exploring the design variations. The parameters that make the design are disentangled by the interface design so that learners can consider design as the exploration of the combinatorial space of independent design features. As users go through a series of designs as they travel through the nodes, the history bar is the way to show them where they have been and where they are now. It allows users to not only

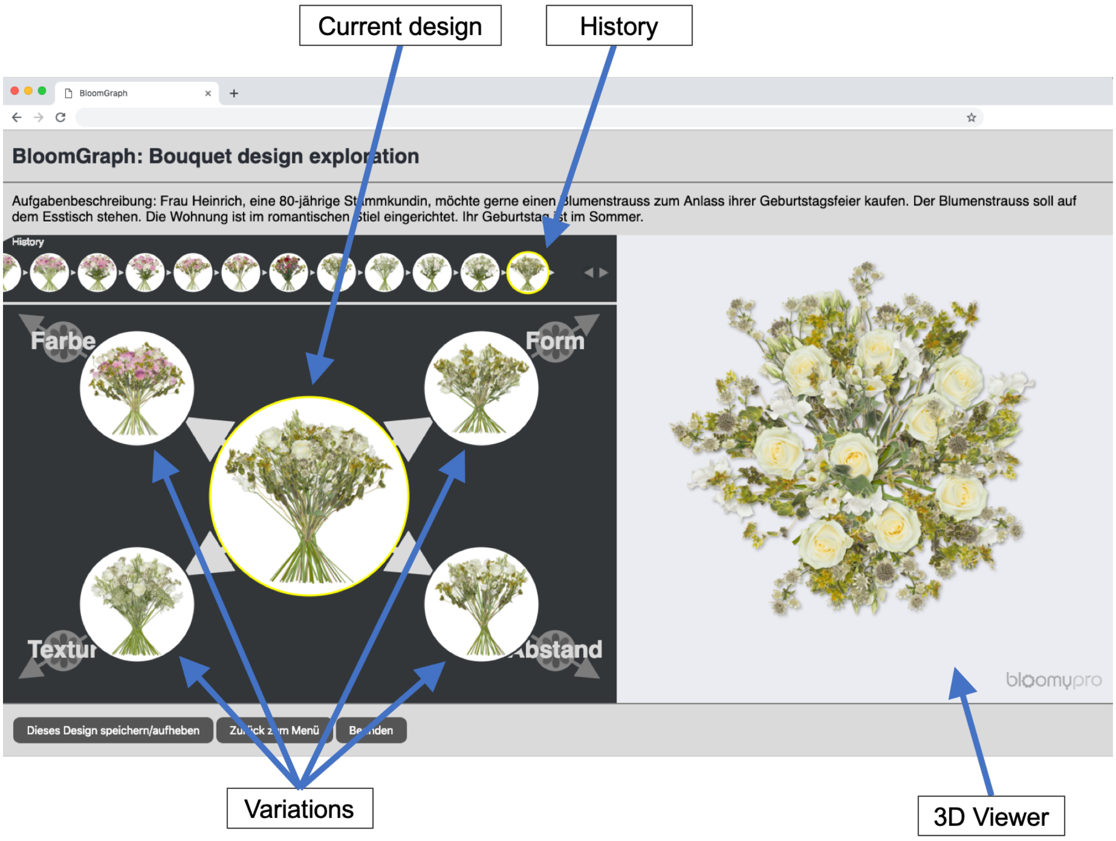

Figure 4.1 – BloomGraph application: The current design is shown in the center of the graph interface on the left. Four variations of the current designs are proposed along the four axes. The history bar shows all the designs that have been explored in the past and allows going back to them. 3D visualization of the current design is shown on the right.

backtrack to previous stages, but also visually see the exploration path while going through the designs.

The BloomGraph application is implemented using Meteor framework written in JavaScript. For the front-end rendering, we used React and D3.js libraries. The interactive 3D viewer is implemented using the API provided by BloomyPro [9].

4.5 Methods

In this section, we describe the details of the experimental study we conducted using BloomGraph and our analysis methods. As mentioned in the introduction, the goal of the experiment is to investigate how florist apprentices would explore the space of design variations given the graph-based interface of BloomGraph.

Participants

In order to recruit the participants for the experiment, we first contacted florist teachers in vocational schools in Switzerland. Four teachers from three schools agreed to run the experiment in their classes. We did not have any criteria for eliminating students and invited all the students from the classes to participate. As the result, 44 florist apprentices (43 females and 1 male) participated in this study and they were aged between 15 and 61 years ($M = 28.4$, $SD = 15.2$). The unbalanced gender ratio comes from the nature of the profession. The wide range of the age is due to one of the classes being a retraining. Thirty-four subjects were in their first year of the three-year program of the basic vocation education and the remainder in their second year. All participants were asked to sign a consent form if they agreed to participate after reading the information sheet. Participants under 18 years old had to provide a signed parental consent form, which had been distributed to them two weeks in advance of the experiment. The protocol of the experiment has been approved by the Human Research Ethics Committee of EPFL.

Experimental design

For the study, we used a between-subjects design with 23 participants in the experimental condition using the graph-based interface of the BloomGraph application and 21 participants in the control condition using the linear-based interface. We controlled for the type of the class and the school year when assigning the participants to the two conditions.

Task and materials

The task for the participants was to select a bouquet design that is most appropriate for a virtual customer. Together with a florist teacher, we developed two scenarios that resemble real-world situations—first scenario for the birthday party of an old lady and the second one for a wedding. The two scenarios are shown in Table 4.1.

For the task, the participants either worked with a graph-based interface or linear-based interface depending on their assigned condition. The graph-based interface was designed as described in the previous section. It disentangles the four dimensions of the design space and presents the bouquets in a structured manner. For the control condition, linear-based interface is used and it is shown in Figure 4.2. In the linear-based interface, four random variations of the current design are proposed in a linear formation. It is the same dataset as the experimental condition, presented in an unstructured way. It resembles the way people go through a catalog or a search result. In order to provide equal amount of information as the experimental condition, each variation in the linear condition comes with a tag that shows which attributes have been changed from the current design. As with the graph condition, to control for the availability of other features, the participants had access to their history and the 3D viewer. The difference between the two interfaces is the way we present the same data

Table 4.1 – The two scenarios used in the experiment.

	German	English translation
Scenario 1	Frau Heinrich, eine 80-jährige Stammkundin, möchte gerne einen Blumenstrauss zum Anlass ihrer Geburtstagsfeier kaufen. Der Blumenstrauss soll auf dem Esstisch stehen. Die Wohnung ist im romantischen Stiel eingerichtet. Ihr Geburtstag ist im Sommer.	Mrs. Heinrich, an 80-year-old regular customer, would like to buy a bouquet for her birthday party. The bouquet should stand on the dining table. The apartment is furnished in a romantic style. Her birthday is in summer.
Scenario 2	Eine junge Frau betritt Ihren Laden, die sie zuvor noch nicht gesehen haben. Sie ist an einem Hochzeitsblumenstrauss interessiert. Die Hochzeit findet im Mai statt und die Braut wird weiss tragen. Sie informiert sie, dass natürliche Blumen und die Farbe Lila mag.	A young woman enters your shop, whom you have not seen before. She is interested in a round handbound bridal bouquet. The wedding will take place at the end of May and the bride will wear white. She informs them that she likes natural flowers and the colour purple.

and it is to test our hypothesis on the effect of a graph interface on the design exploration.

For each scenario, we created a set of bouquet designs. They were created systematically so that users can vary one parameter of the design at a time. Each parameter could take one of three values we designed (e.g., the color parameter, the main theme color of the bouquet, can be either red, pink or write). Combining the three values for each of the four parameters, the dataset consists of 81 bouquet designs per scenario. The images of the bouquet designs are in the Appendix.

To measure the participants' understanding of the design space, we created pre-test and post-test measures. In particular, we wanted to see if they could understand the bouquet design process as a combinatorial problem where a design is a combination of parameters that can take different values. We designed two types of questions—one on identifying the design that shares a parameter value with a given set of designs and the other on identifying the most appropriate design that could be placed in a missing spot in a connected structure of designs. The questions were multiple choice questions and the participants were asked to choose the one that was most appropriate. Each test was made up of five questions of each type and each question was worth 10 points, therefore the maximum score of 100 points. We created two versions of tests and counterbalanced their use as a pre-test and post-test. The details of the tests are provided in the Appendix.

A questionnaire was given at the end of the experiment and it included questions on demographic information and their experience with the BloomGraph application. In terms of their experience with their application, we asked five 7-point Likert scale questions on the usability

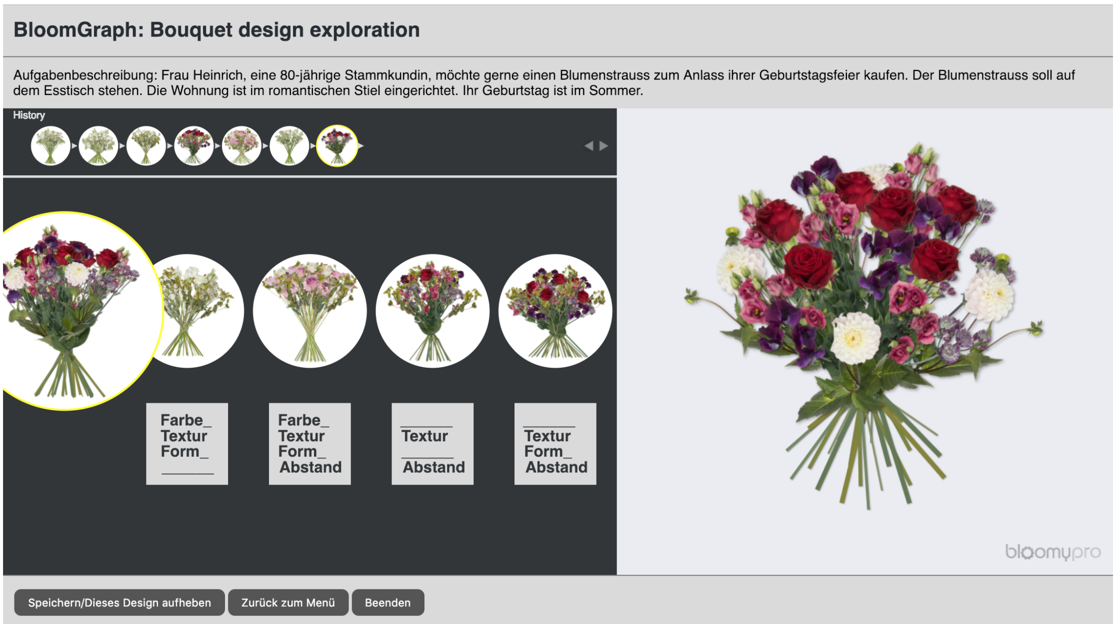

Figure 4.2 – Linear interface for the control condition in the experiment: The current design is shown on the far left of the linear presentation followed by four variations of it. Each variation has a tag that shows which parameters are different from the current design. On the right, an interactable 3D visualization of the current design is shown.

and satisfaction. Additionally, we asked them to provide an estimate for the total number of bouquets in the given dataset for each scenario during the experiment. Estimation on the size of the dataset is one of the factors that reflect the participant's understanding of the given space. The questionnaire is provided in the Appendix.

Procedure

The experiment started with the general introduction of the study. Participants signed the consent form if they agreed to participate. Then they were asked to do a pre-test. Once they finished the pre-test, we went through an example tutorial together so that they could familiarize with the interface. The tutorial was given in the interface that they were assigned to based on the grouping. The example tutorial did not involve flower bouquets, but some simple geometric primitives so that they would focus on the interface, not the designs themselves. Once they finished the tutorial, they were given the actual tasks of selecting the bouquet designs for the virtual customers. They were asked to do two exercises, one for each scenario. The order of the scenarios was counterbalanced. Once the participants completed the two tasks, they were asked to do a post-test followed by the questionnaire.

Measures

During the experiment, we collected data in two ways. All the interactions of the users with the interface of the application have been logged. The log included the designs they went through and the time stamp for each action. Using the log, we can analyze the behavior of users and the strategies adopted by them. In addition to the application log, we recorded the eye gaze of the participants. We used a screen-based eye tracking device from SMI and recorded the binocular gaze at 250 *Hz*. The purpose of the eye gaze recording is to investigate the visual behavior of users. We only recorded the gaze of the participants in the experimental condition as our interest was specifically on the strategic behavior in using the graph interface (RQ2 and RQ3).

Analyses

In order to answer our research questions, we analyzed the data in two parts. The first part of the analysis is to answer the first research question on the effect of the graph interface on design exploration. The second part of the analysis focuses on the behaviors of the participants using the graph-based interface in order to answer the second and the third research questions on the strategies adopted in the graph exploration. Details of the measures we analyzed are described in this section.

In the first part of the analysis, to see the effect of the graph interface on the exploration patterns of the learners, we compared the experimental group with the control group on different metrics: number of bouquets explored before making a choice, number of revisits to the same bouquets, total exploration time, and time spent per bouquet. We also compared the learning gains between the two conditions. We used the difference between the post-test and the pre-test scores as the learning gain. Another factor we looked at is the estimation on how many bouquets they think there were in each scenario. We also investigated the diversity of the bouquets they went through. The diversity measure was calculated for each participant using the concept of entropy as follows:

$$S = -\sum_{i=1}^{N}\sum_{j=1}^{M}\left(p_{ij}\log(p_{ij})\right) \tag{4.1}$$

where N is the number of parameters of the bouquet design and M is the number of values that each parameter can take. And p_{ij} is the percentage of value j for parameter i in all the bouquets that one participant visited. In the experiment, $N = 4$ and $M = 3$.

In the second part of the analysis, we took a closer look at the experimental group in order to investigate the strategies adopted in the graph exploration. As our interest is on the strategy used for navigating different dimensions of design parameters, we looked at the sequences of the parameters that the participants selected, specifically the average number of consecutive clicks on one axis. Higher number of consecutive clicks in one axis means exploring more variations in terms of that parameter consecutively, or going deeper in that dimension. This strategy can be described as more consistent in choices since it has a priority on the consistency in parameters. On the other hand, lower number of consecutive clicks in one axis shows lower consistency in attribute choices. For example, Figure 4.3 shows two click sequences where the colors represent different attributes chosen to be changed. In our definition, Sequence 1 shows more consistent strategy whereas Sequence 2 is less consistent. The purpose of using this measure to characterize the strategy is to investigate the effect of the disentanglement of the dimensions on the exploration paths with respect to the dimensions.

Figure 4.3 – Examples of exploration pattern: Sequence 1 shows the strategy of higher consistency where as Sequence 2 of lower consistency based on our definition. The colors represent different parameters selected to change.

Regarding the third research question, we investigated the visual exploration behavior using eye tracking data. In order to measure how visually explorative they are, we defined visual-explorative-ness with the number of fixations on the four proposed variations before clicking one. This measure shows how much they visually explored the proposed options for making a choice. We looked at the correlation between the visual-explorative-ness and the consistency in the attribute choices in order to investigate the relationship between the visual behavior and the exploration strategy. Lastly, we investigated how we can use the eye gaze data to predict the next click of the learner. We used a support vector machine (SVM) to train the prediction model with the features extracted from the gaze data. We extracted features from the gaze events before each click and generated feature vectors. The feature vector included the number of fixations on each node, the time spent on each node, and the node with the maximum time spent. We randomly selected 80% of the eye tracking data to train the model and the remaining 20% was used to test the performance.

4.6 Results

As described in the previous section, we analyzed the data in two parts and we present the results in this section. For the statistical tests, we used Kruskal-Wallis test due to the non-normality of the distributions of data.

Graph vs. linear interface

Comparing the exploration behavior in the two conditions, we first observed that the number of bouquets participants explored for a task was significantly different, $\chi^2 = 8.60$, $df = 1$,

$p < .01$. In the graph condition, they explored fewer bouquets ($M = 13.2$, $SD = 4.46$) before making their choices compared to the linear condition ($M = 18.5$, $SD = 9.42$). We observed a large variation in the linear condition. In terms of the exploration time, we observed that it was significantly longer in the graph condition, $\chi^2 = 5.71$, $df = 1$, $p < .05$ (for the graph condition, $M = 254.2$, $SD = 97.1$; for linear, $M = 195.3$, $SD = 98.4$). Therefore, with the graph interface, participants spent more time on a fewer number of bouquets. The results are shown in Figure 4.4.

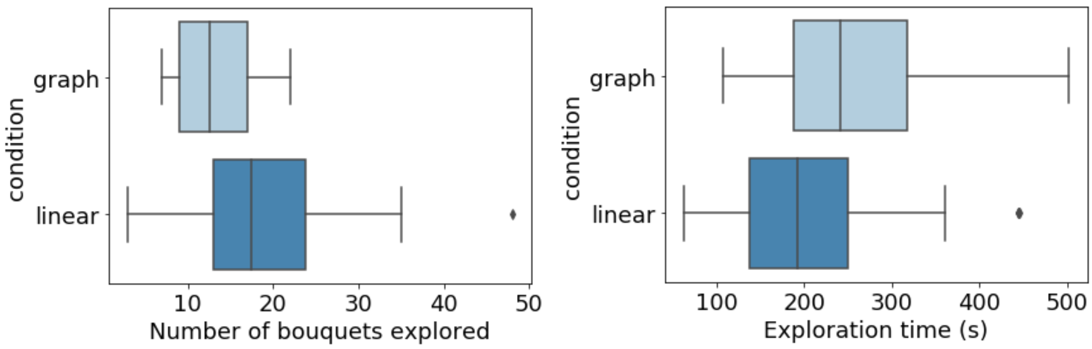

Figure 4.4 – Comparison between graph and linear conditions

In terms of which bouquets the participants visited during the tasks, we analyzed the following factors: (1) diversity of bouquets with the diversity measure defined above and (2) number of revisits to the same bouquets. For the diversity of bouquets explored, we observed a significant difference between the two conditions, $\chi^2 = 5.71$, $df = 1$, $p < .05$, with the experimental group ($M = 2.03$, $SD = 0.21$) showing a higher diversity compared to the control group ($M = 1.82$, $SD = 0.23$). We also observed a significant difference between the two conditions in the number of revisits to the same bouquets, $\chi^2 = 15.6$, $df = 1$, $p < .001$. The experimental group showed a higher number of revisits ($M = 10.5$, $SD = 6.64$) compared to the control group ($M = 5.52$, $SD = 3.54$).

Regarding the effect of the graph-based interface compared to the linear-based interface, we looked at the learning gain and the accuracy of the estimation on the design space size. We observed positive learning gains in both the graph condition ($M = 25.5$, $SD = 27.6$) and the linear condition ($M = 13.4$, $SD = 24.3$), however, the difference between the two conditions was not significant, $\chi^2 = 2.45$, $df = 1$, $p = .12$. The distributions of the learning gains for the two conditions are shown in Figure 4.5.

For the accuracy of the estimation of the design space size, there was a significant difference between the two conditions, $\chi^2 = 12.3$, $df = 1$, $p < .001$. The participants in the graph condition showed significantly better estimation of how many bouquet designs were present in a scenario ($M = 52.8$, $SD = 12.1$) compared to the linear condition ($M = 29.0$, $SD = 14.4$). The actual number of bouquet designs in each scenario was 81.

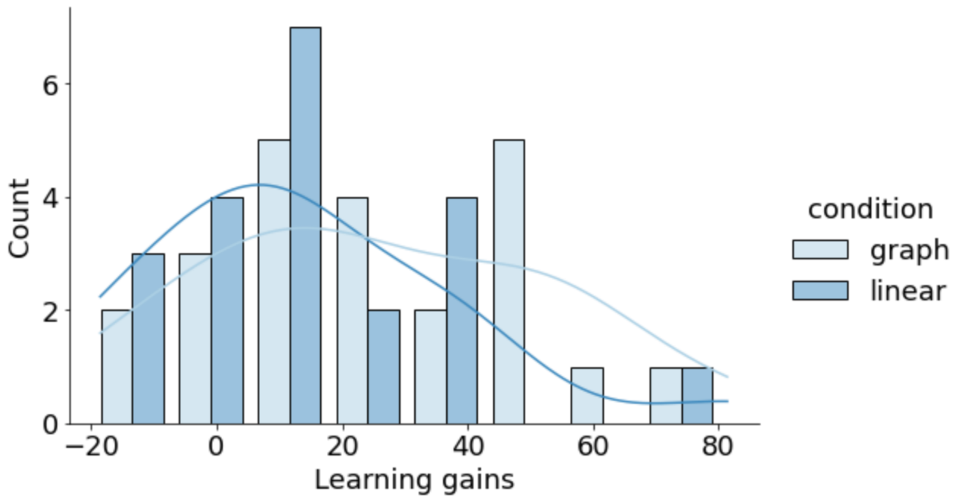

Figure 4.5 – Distributions of the learning gains for the graph and the linear conditions.

Strategies in graph exploration

In order to investigate the strategies of the participants on the graph exploration, we first investigated how consistent they are in terms of their choice of the bouquets in the graph axes. Figure 4.6 shows the sequence of clicks in the graph condition. Using the measure of consistency defined in the previous section, we divided the participants in the graph condition ($N = 23$) into two groups. The group with higher consistency ($N = 12$) had 3.03 consecutive clicks in the same axis in average ($SD = 0.81$) and the group with lower consistency ($N = 11$) 1.45 clicks ($SD = 0.17$). The difference was significant, $\chi^2 = 16.5$, $df = 1$, $p < .001$.

With the categorization based on the consistency measure, we observed that the group of higher consistency ($M = 38.6$, $SD = 24.4$) had significantly higher learning gains compared to the group of lower consistency ($M = 11.3$, $SD = 24.3$), $\chi^2 = 5.77$, $df = 1$, $p < .05$. Figure 4.7 shows the learning gains of the two groups as well as that of the linear group. The difference between the high consistency group and the linear group ($M = 13.4$, $SD = 24.3$) was also significant, $\chi^2 = 7.26$, $df = 1$, $p < .01$. Furthermore, another measure we looked at with respect to the exploration strategy is the estimation of the space size. We noticed that the consistency of their exploration was positively correlated to the accuracy of the estimation ($r = 0.48$, $p < .05$).

Using the eye tracking data, we investigated visual exploration behavior of the participants. The group of higher consistency showed the visual-explorative-ness of 1.82 ($SD = 0.45$) and the group of lower consistency 2.41 ($SD = 0.35$). As individuals, we observed that the visual-explorative-ness is negatively correlated to the consistency in choices, $r = 0.57$, $p < .05$. In other words, the participants with higher consistency in attribute choices were also visually focused on each axis at a time. This result is logical and as expected since in order to be more divergent in choices, one would consider more options visually.

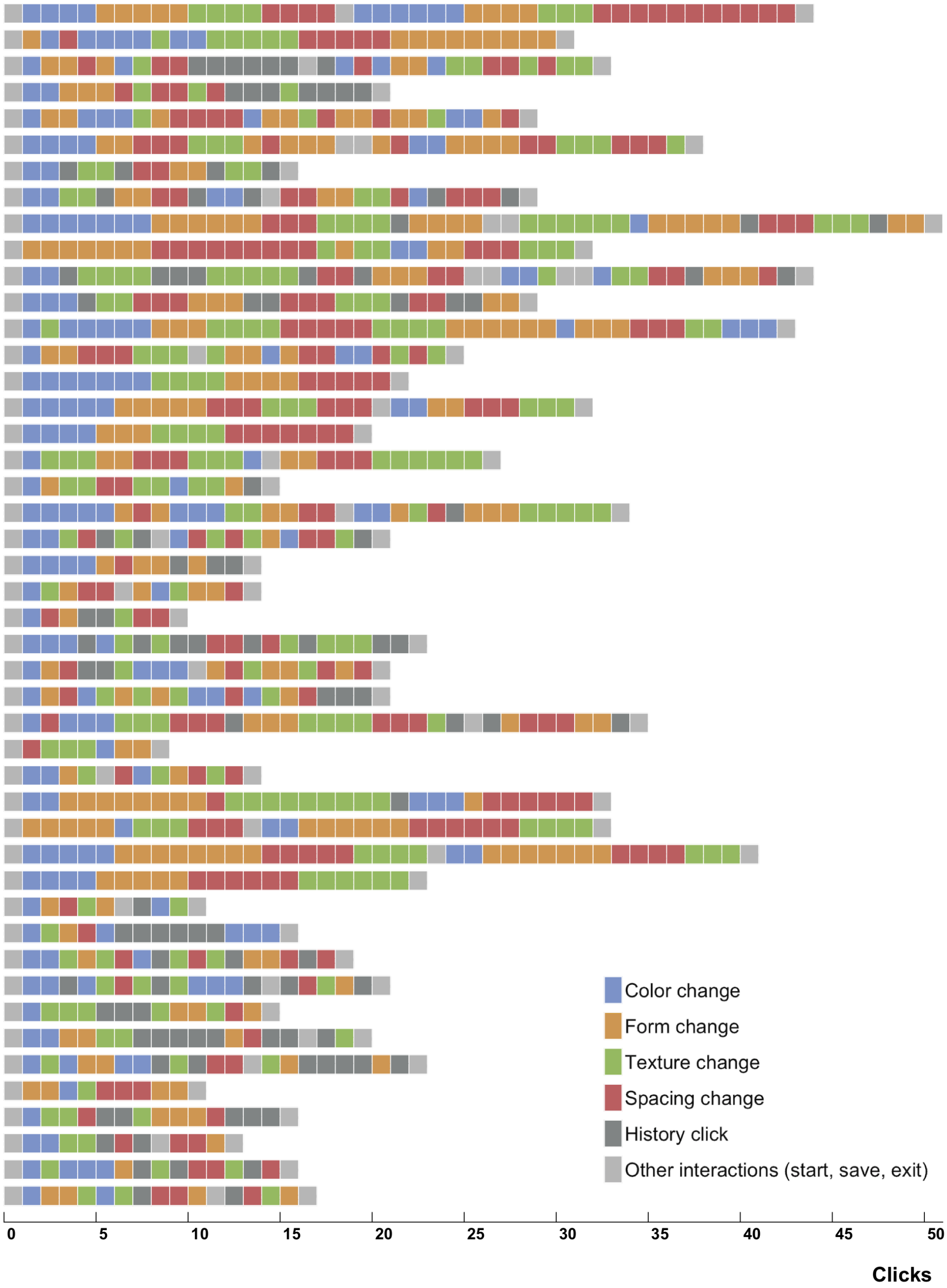

Figure 4.6 – Sequences of clicks in the graph condition: Each row represents one trial and the colors represent different parameters selected to change. Note that the lengths of the sequences show the numbers of clicks, not the time.

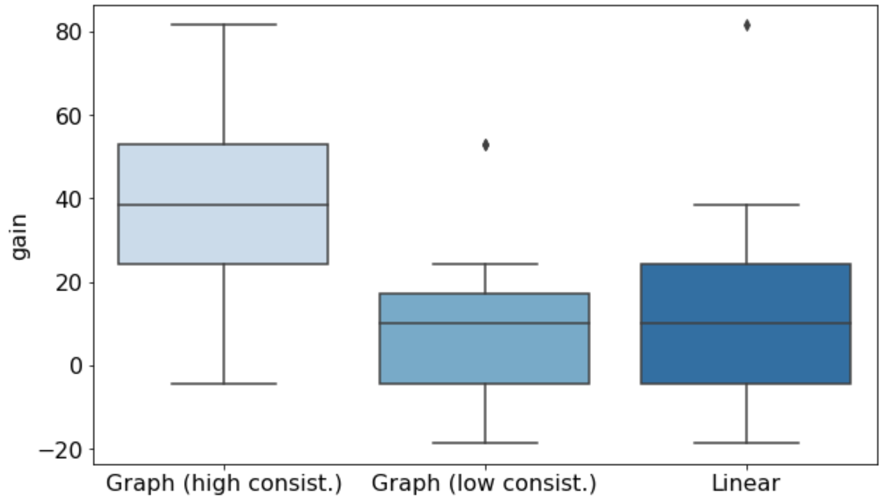

Figure 4.7 – Comparison of the learning gains of the two groups from the graph condition along with the linear condition: The two groups from the graph condition are based on consistency measure of their exploration strategies. The learning gain is calculated as the difference between the pre-test and post-test scores.

Using this correlation observed between the gaze behavior and the choices they make, we investigated whether we can predict the next choice in the navigation based on the eye gaze data. We trained a prediction model using SVM, as described in the previous section. This was done with different grouping—first on all participants in the graph condition then separately for the two groups with different strategies. In order to see how early we can predict a learner's next choice, we made the prediction every 2 seconds up to 12 seconds. The average interval between two clicks was 11.2 seconds. Figure 4.8 shows the test result of the prediction models. The prediction accuracy for the group of higher consistency is the highest among the 3 groups and it reaches approximately 80% after 10 seconds. Overall, all 3 groups show a reasonable performance and the prediction accuracy reaches over 70% in 10 seconds.

4.7 Discussion

In this chapter, we explored the concept of expanding experience in the parametric dimension. We designed a tool called BloomGraph that allows florist apprentices to explore digital variations of bouquet designs while providing an interface to support the navigation. Using BloomGraph, we conducted an experimental study with florist apprentices in order to answer three research questions on: (1) the effect of a graph-based interface, (2) the strategies adopted by the participants in the graph exploration, and (3) the relationship between the gaze behavior and the exploration strategies..

Regarding our first research question on the effect of the graph interface on the design exploration, the analysis allows for a number of observations. First, the participants in the graph

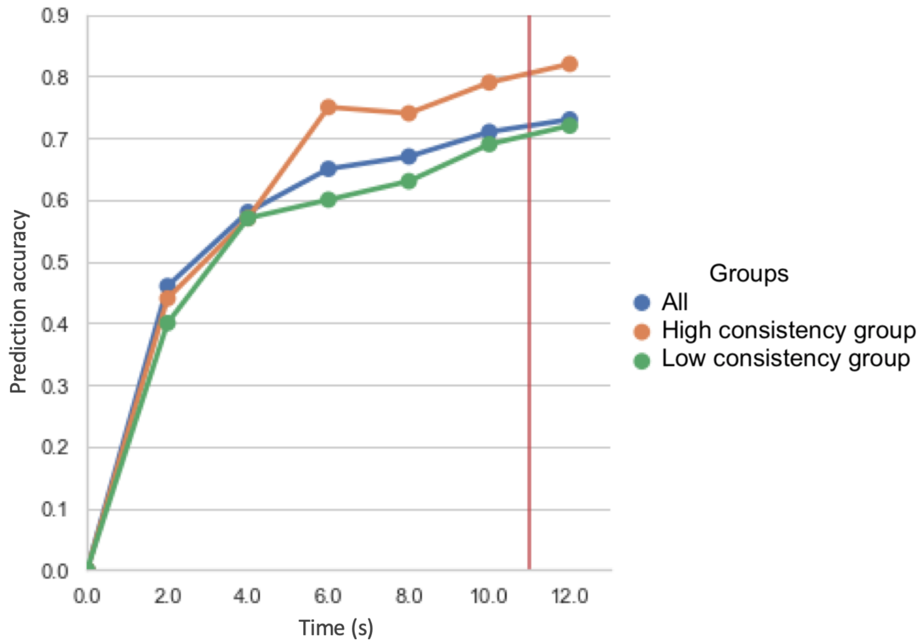

Figure 4.8 – Prediction result on the attribute choices: Prediction is made every 2 seconds. The red vertical line shows average time taken before a click.

condition went through fewer number of bouquets before selecting final designs, compared to the ones in the linear condition. This is logical since the graph allows more direct navigation than the linear presentation. It is debatable whether it is better to navigate efficiently to the goal design or to be exposed to more designs [50, 80]. But what it shows us is that the apprentices were able to navigate using the graph and find their ways more efficiently. In terms of time, they spent more time on the intermediate bouquet designs before making their final choices. This also gives a hint that they are not just randomly selecting next ones on the graph, but trying to understand the structure. In terms of which bouquets they went through, the participants were exposed to more diverse designs when using the graph-based interface. The graph group also showed a higher number of revisits to the same designs while exploring. Overall, we interpret these observations as the evidence of some strategy-driven behavior in the exploration that has been further investigated in the second part of the analysis. In terms of the understanding of the design space, the participants who used the graph-based interface provided significantly better estimations on the size of the design space after the activity. In summary, the graph-based interface led to more efficient navigation towards the goal, exposure to more diverse designs, and better understanding of the design space. These results are in agreement with the previous findings on the advantages of structured and systematic design exploration in design-related learning [72, 101]. Our findings show that the graph-based interface can support the design exploration and that the effectiveness of such design exploration tool can be valid for VET learners.

The second research question was on the strategy in the graph exploration. With the grouping of the participants of the graph condition based on how consistent they are in terms of their choices of attributes, we observed some interesting results. The participants with more consistent strategy showed higher learning gains and they also had better estimation on the size of the design space. Consistency in the graph exploration appears to be an effective strategy that leads to a better learning outcome in our measures. One possible explanation is that the disentanglement of dimensions allowed disentangled exploration which lead to a better understanding of the design space. On the other hand, the participants who had the strategy with lower consistency were less successful. Their behavior can be also seen as jumping among different attributes and trying to be opportunistic in finding what they like. It can be also interpreted as less strategic in the exploration. These results are in agreement with the findings of Ball et al. [8] and Najar et al. [85] on the advantage of strategic approach in design exploration. A schema-driven approach in example search can be more desirable in a design-related task and our study demonstrates it in terms of the understanding of the design space.

The third research question was about whether the behavior of the learners can be predicted using the gaze data. We observed that there was a correlation between the visual exploration behavior and the choices they make for navigating the design using the graph interface. And we trained a prediction model that predicts the next bouquet choices with a reasonable accuracy using the visual features from eye tracking data. One potential use of the prediction model in the context is to provide online feedback to the learners in order to support them with navigating the designs. To summarize the findings from the second and the third research questions, the strategy adopted by the learners in the graph exploration had a significant effect on the learning outcome in our experiment and the visual behavior provided additional insight into their exploration strategy which opens new possibilities for future studies.

Based on our analysis, the participants in both conditions showed positive learning gain from the BloomGraph activity in terms of understanding of the design space. This finding supports the idea of design space exploration as a means of enhancing the learning experience of VET apprentices while demonstrating another practice of the Erfahrraum model. When we focused on the participants with graph-based interface, we observed that some of them benefited more from having the structured way of navigation. We found that the exploration strategy adopted by the learners had a significant effect on the learning outcome. The question to be addressed now is how we can guide the learners so that they can maximize the benefit they take from the activity. The result of the prediction model is interesting in this aspect as it can be used to provide online feedback to the learners as mentioned above. With automated online feedback integrated in the tool, we can guide the learner so that they can adopt a more desirable strategy for the exploration. It would be interesting as future work to investigate the effectiveness of different types of feedback such as direct/indirect or immediate/delayed feedback in this context [18, 102].

The question we had before conducting the experimental study was whether the apprentices in vocational education can understand conceptual design as a combinatorial problem of different design parameters and navigate through them using a graph interface. This might sound as a trivial problem, but it might not be the case for the apprentices in vocational education as the process requires a certain level of abstraction. One might argue that designing a bouquet is not a problem to be approached scientifically, but rather with a free mind of creativity. However, creativity is not unrelated to the understanding of the design space. Understanding what is available as a designer with the awareness of the constraints that exist in the problem space is an important aspect for creativity [52, 104]. We believe that fostering a better understanding of the design space through supporting design exploration has a positive impact on the creativity in a design task.

Although this work contributes to our understanding of designing digital activities for VET learners, there are limitations to the study that should be considered and addressed in future work. We investigated the feasibility of design exploration for VET learners while focusing on their behavior. As we validated the feasibility of the idea, the next question is on how to design and integrate such activity to the learning journey of VET students. It is another research question of how it can be used to enhance the learning experience in a broader scale and it needs further investigation. It requires exploring the fit of such digital activity to the dual-track VET systems, especially in connection to the real-world experience. Another factor to be explored is the generalizability of the results to other professions. While the current study focused on florist education, there are many design-related professions that could benefit from design space exploration and the cross-profession generalizability will be an interesting factor to investigate. In this aspect, we explore another profession in the next two chapters.

This chapter demonstrated an implementation of expanding experience in the parametric dimension using digital design variations provided by a tool. The contribution is the validation of the idea with florist apprentices and we showed how we can support the process by investigating the effect of a structured interface and the exploration strategy. Our results show that the apprentices can benefit from such activity by acquiring a better understanding of the design space and the learning outcome can be further improved by a structured interface as well as the strategy adopted in the exploration. The results support the potential of design exploration as a means of enriching the learning experience of VET learners.

5 Temporal expansion: GardenVR

This chapter explores the temporal dimension of expanding experience. To design a tool for gardener apprentices, we have chosen to use the VR technology as it can provide an immersive environment for them to simulate and experience how a garden design would change in time. In this chapter we present GardenVR, an immersive VR (IVR) tool for creating and exploring garden designs. In an experimental study conducted with gardener apprentices using GardenVR, we investigate the potential of the VR interface as a design support tool compared to a more traditional method of practice, paper sketch. We also analyze how the apprentices explore the time dimension and how their exploration behavior is related to the final design outcome.

This chapter corresponds to the following publication:

Kim, K. G., Oertel, C., Dobricki, M., Olsen, J. K., Coppi, A. E., Cattaneo, A., & Dillenbourg, P. (2020). Using immersive virtual reality to support designing skills in vocational education. *British Journal of Educational Technology*, 51(6), 2199–2213 [58].

5.1 Introduction

Virtual reality (VR) technology has become popular in recent years and its effectiveness has been explored in various educational settings [83]. A potential advantage of VR is that it can encourage students to be active learners and promotes decision-taking by permitting autonomous exploration and learning by doing [81]. VR technologies are capable of promoting a full student-centered learning experience given that students are the main performers when experimenting and practicing with virtual objects [131]. Previous studies show that VR can support learners in terms of academic performance [3, 83], spatial skills [40, 73], social skills [126], motivation [41], and engagement level [23, 81].

However, while many studies show the effectiveness of VR technologies across learning contexts and domains, the potential of VR for VET has not yet been explored in-depth. VET systems are based on the idea of learning through situated experience and many learners do an apprenticeship in companies where learning is often embedded in their workplace. For example, a florist should design a bouquet based on a specific request of a customer, or a carpenter should be aware of the safety information in a particular construction site. VR can offer possibilities of creating these situations for the learners in a safe, exploratory practice space [71]. Particularly, immersive VR (IVR), compared to the conventional monitor-based low-immersion VR, can potentially enhance learning through situated experience with greater immersion, learning through multiple perspectives, and transfer through simulations of the real world [23].

In this chapter, we present an IVR application we developed for gardener apprentices and investigate its effectiveness for supporting them in a design task. Through an experimental study, we compared IVR with current paper-based practices and investigated how they may be effectively combined to support design outcomes. We are interested in the comparison between IVR and paper since we believe that both interfaces have their own specific affordances that learners can benefit from. We also investigate the combination of the two in order to verify if the strengths may be complementary depending on how they are combined. Furthermore, we investigate more closely how the apprentices explore the time dimension of their designs while using the IVR application.

5.2 Related Work

VR can provide learners with the opportunity to experience situations that cannot be accessed due to factors such as time problems (the inability to speed up/slow down or go back in time), physical inaccessibility (places or situations that one cannot be in), dangerous situations, or ethical problems [33]. In VET, this opportunity to experience inaccessible situations can be particularly effective for supporting learning. For example, Webster [129] studies IVR in the domain of corrosion prevention/control and demonstrates its effectiveness on learning gains compared to traditional lecture-based learning. VR can also simulate dangerous tasks to support learning of construction safety [71] or in the engineering sector [97]. As these examples illustrate, VR technologies are capable of allowing VET learners explore the situations that are difficult to directly observe and experience in the physical world [89, 96].

Particularly for designing skills, IVR has shown positive effects. Researchers have demonstrated the effectiveness of immersive environments for designing airport interiors [55], creative form-making in visual art [54], designing DNA molecules [106], and evaluating machinery designs [6]. In these studies, the purpose of IVR was often the assessment of a design prototype or communication with customers. On the other hand, Rieuf et al. [100] investigated the effect of IVR on the quality of design outcomes and found that the use of IVR for early-stage product design is effective for aesthetics and originality of the final design. However, their experiment was designed for experienced designers and the analysis focuses on the emotional influence of the IVR activity on the design outcome. It is still an open question of how IVR can support the design skills of novices as measured by the quality of the design outcome, which is the focus of our study.

This further investigation is particularly needed as there is conflicting evidence across domains as to the effectiveness of IVR. Previous research has shown IVR to positively influence motivation and attitudes towards learning [69, 78, 92]. On the other hand, IVR has been reported to have negative effects on cognitive load [79]. In terms of learning, IVR introduces possibilities for unique representations of situations that are not available in conventional methods currently used in classrooms, such as the standard of paper-based practice. IVR provides learners with the ability to change their perspective and frame of reference, which is a powerful means of understanding complex phenomenon or structures [23] and can improve learners' spatial understanding [40, 73].

Additionally, previous research has explored the effectiveness of IVR in terms of running realistic simulations while comparing it with physical ones. There is ongoing debate about the pedagogical value and the benefit/loss of replacing real physical experiences by the virtual ones. Some previous studies show that IVR simulations can be as effective as physical ones, despite the lower number of interaction channels (e.g., without haptic or smell) [61, 134]. Consideration on the effective transfer from the virtual experience to the real one has naturally led to building virtual environments as perceptively quasi-identical to the reality (i.e., high resolution images, surrounding sounds, and etc.), based on the hypothesis that higher the feeling of immersion is, the better the transfer to reality will be. However, it has also been shown that higher immersiveness can result in increased cognitive load leading to less learning [79].

Our focus in this study is on exploring the difference between what is possible in the virtual world and in the real world, rather than trying to make the virtual environment as close to the reality. VR provides learners with the opportunity to manipulate factors that cannot be changed in real-life, such as the passage of time [33, 79, 92]. In designing tasks in particular, these affordances may allow learners to focus on the spatial aspects of the design and how they may change over time [40, 73] providing a strong case for the use of IVR in garden designs. On the other hand, paper sketches are a familiar medium to students, which can lower the extraneous cognitive load of students working with the material [127]. With a lower cognitive load, learners have more opportunities to develop knowledge towards the learning outcomes [79]. These differences between IVR and paper interfaces may influence the effectiveness of the activity depending on how the affordances align with the goals of the task.

Moreover, these differences may provide complementary benefits depending on how the representations are combined [2, 128]. Combinations of VR with physical practice can be more effective than either one of them alone [22, 49, 65]. VR and physical practice each provide different representations that when combined can more effectively support learning [1]. Moreover, how the representations are combined, i.e., the order in which the learners interact with them, may influence learning [2]. In this case, it is not just a question of if a combination is more effective, but what order is most effective.

5.3 Research Questions

For this study, we investigated how IVR can support the designing skills of VET learners. Specifically, we chose to work with gardeners as their work involves designing physical spaces and the time dimension is important in their designs, which aligns well with the affordances of IVR. We were interested in measuring the quality of the apprentices' designs using an IVR application in comparison with a paper sketch and how the quality is affected by a different order in combining of the two modalities. Sketching-on-paper is a legitimate baseline for the study as it is how gardener apprentices practice designing in schools. We were also interested how the apprentices would explore the time dimension of the designs using the IVR application and how their behavior is related to design outcomes. For this investigation, we formulated our research questions as follows:

- RQ1: Can an IVR interface support designing skills compared to a paper interface and in which ways does it differ in terms of the quality of design outcome?
- RQ2: In what ways do learners improve their designs with a chance to iterate and does the order in which they interact with the IVR compared to the paper sketching impact their design quality?
- RQ3: What are the behavior features from IVR that are correlated to the design outcome?
- RQ4: How do learners explore the time dimension and how is their time navigation strategy related to the design outcome?

The first question investigates the feasibility of using IVR to support designing skills by comparing it to the conventional way of practice. We hypothesized that the IVR interface can better support the designing skills compared to the paper interface and improve the quality of the design outcome in terms of proportion, composition and creativity (H1). These criteria have been chosen with gardening teachers while considering the affordances of IVR in the domain and this hypothesis is based on the positive effects of VR on spatial skills and creative designs [40, 73]. The second question investigates how to combine IVR with conventional practice in order to maximize its benefit. We hypothesized that the quality of design would improve in the second activity compared to the first (H2a) and that learners would have a better design quality in IVR if it was done after the paper sketching (H2b). These hypotheses are based on the positive findings of Rieuf et al. [100] on the effect of IVR in the design process. The third question is on the investigation of the learner's behavior while using the application. We hypothesized that the design quality is positively correlated to the time spent on designing, the number of objects placed in the design and the number of time simulations run (H3). Lastly, the fourth question focuses on how learners explore the time dimension. We hypothesized that there is a different in the time exploration behavior between the learners who produce higher-quality designs and the ones with lower-quality (H4).

5.4 GardenVR

5.4.1 Design

The IVR application used in this study, GardenVR, supports learners in practicing and developing designing skills through designing a garden and exploring it in an immersive environment. In order to maximize the benefit of IVR in a garden designing context, we developed GardenVR based on the following concepts: (1) multiple perspectives, (2) constructivism, (3) going beyond physical limits, and (4) expanding a real-world experience.

Multiple perspectives

The benefit of having multiple perspectives in a creative task has been well reported in the literature [4, 21] and the ability to change one's perspective in IVR is a powerful means of understanding complex phenomenon or structures [23]. This is usually done by allowing shifting between exocentric and egocentric views. In GardenVR, we provide two modes for learners that they can switch between. The two modes, Design and Explore, are shown in Figure 5.1 and Figure 5.2. The Design mode provides an exocentric view where the learners are given the top view of the garden and they can place objects such as trees in the garden. The top-view exocentric perspective for designing is inspired by how gardeners work with 2D top-view drawings on paper or in CAD software to represent a garden. On the other hand, the Explore mode provides an egocentric view where the learners are inside the garden that they designed. They can explore the garden by walking through it in a 360-degree 3D environment. By switching between the two modes, the learners can experience different perspectives on the design.

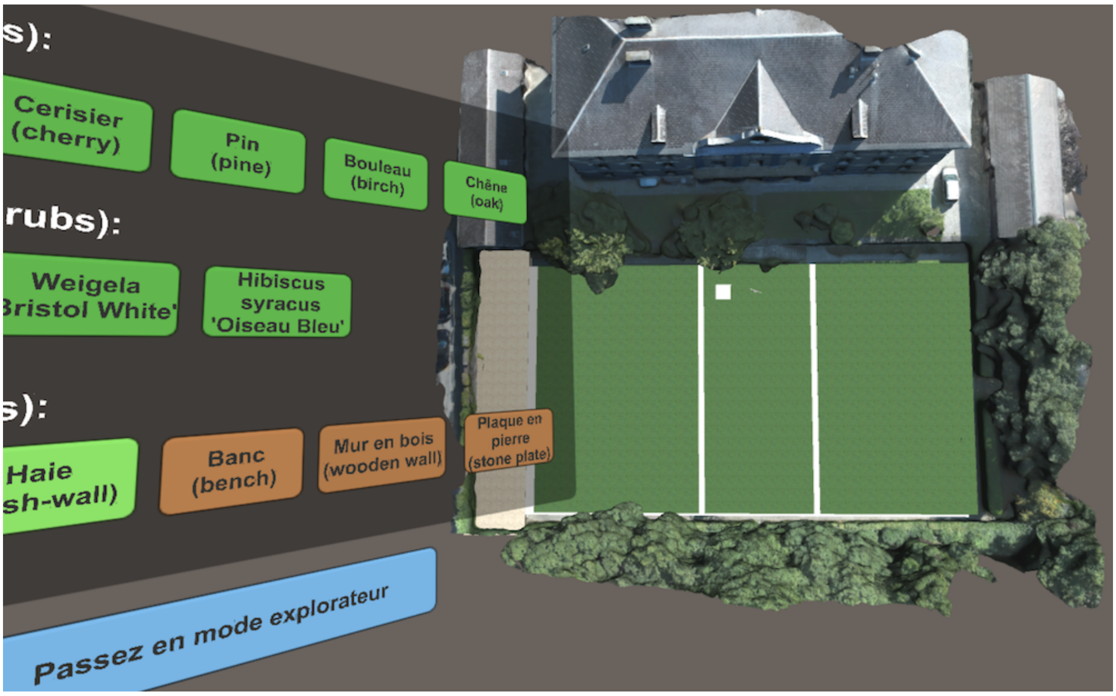

Figure 5.1 – Design mode with an exocentric view

Constructivism

VR technologies encourage students to be active learners by promoting decision-taking, permitting autonomous exploration, creating new experiences, and learning by doing [81], thus aligning with the constructivist approach [131]. In GardenVR, learners are given a practical task of designing a garden where they are the main performers of the task. They create a garden and experience it themselves, which is very similar to their real-world work. However, an advantage of the virtual environment is that learners can easily undo an action allowing them to practice trial and error as the main performer. They can try an action (e.g., planting of a tree), observe the consequence, and undo the action. For a profession like gardeners, it is not feasible to take this approach for training in the real world, if not impossible.

Going beyond physical limits

One of the motivations for the use of VR is the opportunity to experiment with those situations that cannot be accessed physically. For GardenVR, we focus on the time dimension. One of the skills that gardener apprentices need to acquire is the ability to consider the evolution of the garden over time. In garden design, there are three important time scales: daily changes of the Sun's position and the shadows, seasonal changes of plants, and the growth of trees in years. GardenVR provides the functions of daily, seasonal, and yearly changes of the gardens. Figure 5.3 shows screenshots of the time exploration using GardenVR. Learners can fast-forward the time to visualize the evolution of the garden supporting the advantage of VR-based simulations

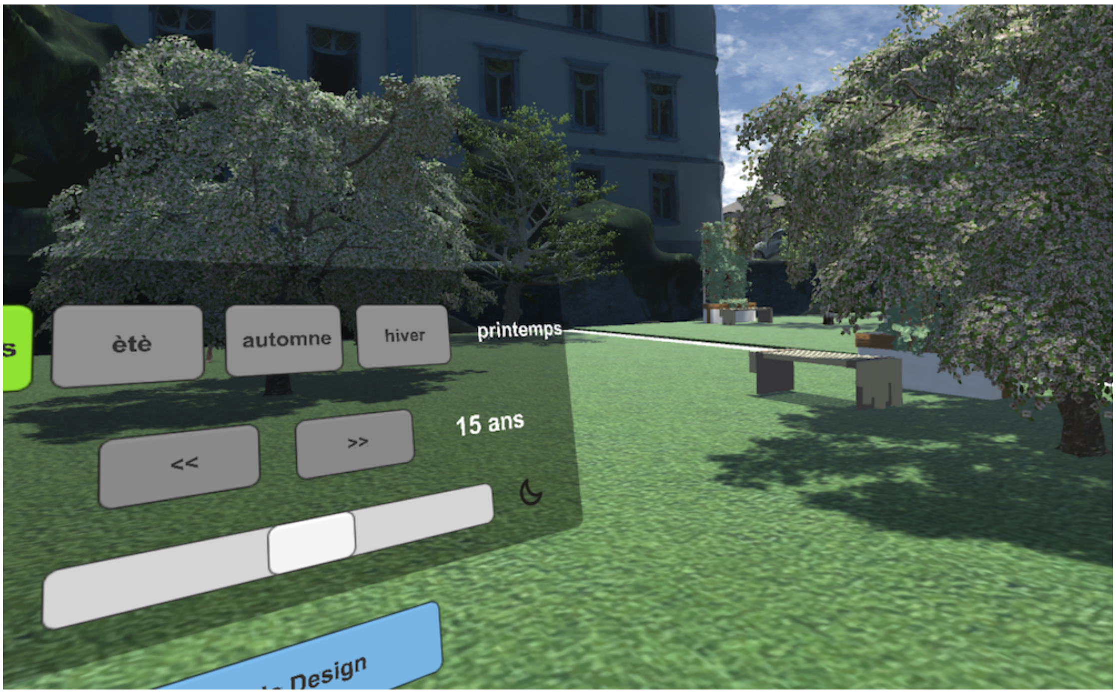

Figure 5.2 – Explore mode with egocentric view

to reduce the time demand for experiments [79].

Expanding a real-world experience

As the other tools presented in this thesis, the purpose of GardenVR is to expand a real-world experience of VET learners. An experience from real life is the starting point of the digital experience. In order to connect the digital experience to a real-world experience, GardenVR uses a 3D scene captured from the real world for its design activity. As shown in Figure 5.4, we use the photos taken from a drone to reconstruct the 3D environment of a real-world site and import it into the tool. In this way, the digital experience provided to the apprentices by GardenVR is built on their real-world experience and expanding it.

5.4.2 Interface and implementation

The interface of GardenVR is designed for a head-mounted display with two controllers for both hands. Using the right-hand controller, one can point at an object and interact with it. On the left-hand controller, a menu is attached that shows the available functions. In the Design mode, the menu shows the objects that can be placed in the garden, and in the Explore mode, it shows the options to explore the designed garden including changing seasons and growing trees. In the Explore mode, one can also move around in the garden using the thumb

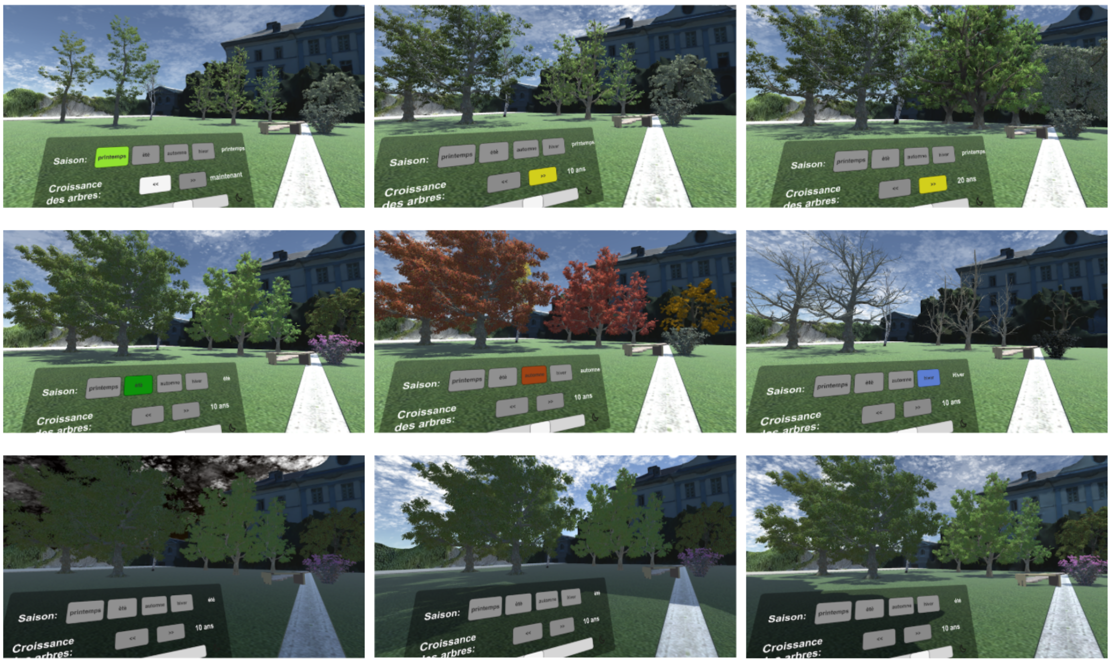

Figure 5.3 – Time exploration using GardenVR: Changing the hour of the day (*bottom row*), the seasons (*middle row*), and the years (*top row*)

stick on the left-hand controller. The GardenVR application was developed for Oculus Rift[1] using the Unity 3D environment[2]. The 3D models of the trees are created using SpeedTree[3].

5.5 Methods

Research design

In order to test our hypotheses, we conducted an experiment with a 2 by 2 mixed-subjects design where the interface (paper or IVR) was the within-subjects factor and the order of the interfaces was the between-subjects factor. The participants were assigned randomly to either paper-first condition or IVR-first condition. The task given to them was to design a garden room in their school garden. The participants were asked to do the task using the two interfaces and the order was based on the conditions in which they were assigned. The experimental protocol has been approved by the Human Research Ethics Committee of EPFL.

[1] https://www.oculus.com
[2] https://unity.com
[3] https://speedtree.com

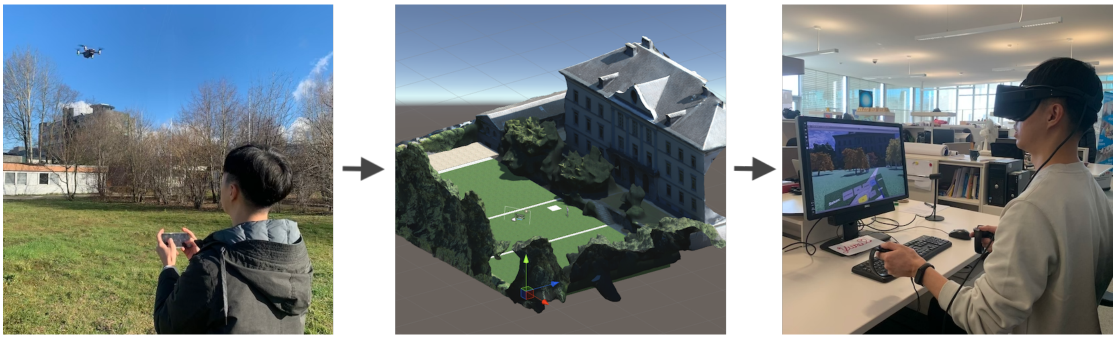

Figure 5.4 – Workflow of GardenVR. Taking pictures of a garden with a drone (*left*), 3D reconstruction of the space (*center*), and designing activity in IVR (*right*)

Participants

We conducted the experiment with 30 gardener apprentices from two schools in the dual-track VET system in Switzerland. Considering the relevance of the task to the curriculum, we only recruited students who are specializing in landscaping, but not in plant production. We also limited our sample to the second-year students in the three-year curriculum for the homogeneity of the population.

The participants were aged between 16 and 30 ($M = 20.2$, $SD = 4.16$) and 26 of them were male. The unbalanced gender ratio comes from the nature of the profession. They have learned the design rules for gardening for two semesters, but have limited experience in designing gardens themselves. Among the 30 participants, we randomly assigned 14 to the paper-first condition and 16 to the IVR-first. There was no significant difference between conditions with respect to age range, $F(1,28) = 0.980$, $p = .33$. All participants were made aware of their rights before participating in the study and consent was collected.

Experimental procedure

When the participants arrived, we gave them a general introduction to the study and asked them to read and sign the consent form. Before working with either of the interfaces, the participants read through an instruction sheet that described the task—to design a garden room for an empty space in the school garden. They were also given a set of trees and objects that they could use in the design. The participants were asked to do the task using the two interfaces based on the order to which they were assigned. For the paper interface, they were given a sheet of paper with the design area marked as a rectangle and the scale information. They used a normal pen or pencil to make a sketch. For the IVR interface, they were given a short tutorial on how to use the IVR device in order to design a garden. For each interface, they were given 25 minutes in which to design their garden.

Dependent measures and logs

We were mainly interested in the quality of the garden design created by the participants as a measure of performance. In order to quantify the quality of the designs, we used the evaluations of domain experts as they play an important role in evaluating creative work [53]. We asked two gardening teachers from a Swiss vocational school who had more than ten years of experience in the field for grading. They had a design review meeting and agreed on the grades for each design in three criteria: proportion, composition and creativity. Proportion refers to the spatial relationship among the objects, composition is about the appropriateness of the selection of the objects, and creativity is about how creative the design is within the boundary of the basic design rules. The first two criteria, proportion and composition, directly involve domain-specific knowledge. For creativity, previous research shows that domain-specific expertise is crucial for creativity assessment [7]. For each criterion, a grade was given from 0–7. During the meeting, any grades that were inconsistent between the two teachers were discussed until agreement was reached.

In addition to the design outcomes, we collected log data while the participants were using GardenVR. The log data included all the interactions of the participants with the application. Each action of a participant was recorded as one line in the log file and it included timestamp, type of the action, objects involved in the action, and the mode in which the action occurred. In addition to the action logs, we also recorded the 6-DOF positions of the participant's head and the two hands in the virtual space. The position log was recorded every second.

Analysis

To investigate the effect of the interface and the order on the quality of the design outcome, we conducted a repeated measure ANOVA analysis. We analyzed the difference between the two interfaces as well as the effect of the order of them while considering the interaction effect. To assess the combination of the IVR and paper activities, we conducted a t-test to compare the performance between order groups on the second activity. We used the p-value of .05 for the significance level and we measured the effect size using partial eta-squared (η^2) value where 0.01 is considered a small effect size, 0.09 a medium effect size, and 0.25 a large effect size.

In order to investigate the behavior of the participants using GardenVR, we analyzed the log data collected. From the log data, we extracted a number of process variables including the time spent in the two modes measured in seconds, the proportion of the time spent in the two modes, number of objects placed in the design, number of revisions of the design, and the number of the time change simulations executed in the Explore mode. Using Pearson's correlation, we investigated how these variables are related to the quality of the design outcome. We also looked more closely into the time exploration behavior of the participants and investigated how it is related to the design outcome by comparing two groups with high and low quality of final designs.

5.6 Results

Hypothesis H1: Effect of IVR interface

We first investigated the effect of the interface on the grades in the three criteria. The descriptive statistics are shown in Table 5.1. For the proportion grade, the results indicated a main effect of the interface, $F(1,27) = 8.92$, $p < .01$, $\eta^2 = .24$, with the IVR condition outperforming the paper. For the composition grade, there was not a significant effect of the interface, $F(1,27) = 0.27$, $p = .61$. For the creativity grade, we observed a main effect of the interface, $F(1,27) = 13.17$, $p < .01$, $\eta^2 = .32$, with the paper condition outperforming the IVR. However, we observed significant interaction effects between the two factors in all three criteria (for proportion, $F(1,27) = 14.24$, $p < .001$, $\eta^2 = .43$; composition, $F(1,27) = 23.04$, $p < .001$, $\eta^2 = .50$; creativity, $F(1,27) = 24.28$, $p < .001$, $\eta^2 = .50$). As shown in Figure 5.5, the quality of design within an interface changed depending on the order. In this case, we cannot claim that IVR or paper outperforms the other on proportion or creativity respectively as there may be a confound of the combination. As the analysis comparing the outcomes of the second activity to investigate the impact of the combination orders will occur to answer H2b, we only conducted a post hoc analysis to compare the outcomes of the interfaces after the first activity. We found no significant difference in terms of proportion, $t(28) = 1.51$, $p = .14$. However, we found a significant difference for both composition, $t(28) = 4.42$, $p < .001$, $\eta^2 = .41$, and creativity, $t(28) = 6.00$, $p < .001$, $\eta^2 = .56$, with paper outperforming IVR. In summary, our analysis showed that the IVR interface can be more effective for the proportion aspect, but this may be limited to students that are able to use it after working with paper. On the other hand, the paper interface was better for the creativity of the design only partially confirming our hypothesis (H1) around the benefits of IVR compared to paper.

Table 5.1 – The grades in three criteria for the IVR and the paper interfaces, Mean (SD).

	IVR		Paper	
	As 1st	As 2nd	As 1st	As 2nd
Proportion grade	3.06 (0.57)	3.71 (1.07)	3.43 (0.76)	2.13 (1.15)
Composition grade	3.06 (0.93)	4.14 (0.86)	4.57 (0.94)	2.94 (1.34)
Creativity grade	2.81 (1.22)	4.14 (1.29)	5.36 (1.08)	3.69 (0.95)

Hypothesis H2a: Design improvement with iteration

Our second research question was whether learners improve their designs with a chance to iterate. In other words, did they improve from the first to second activity. The results indicated that there was not a significant difference between the grades of the first and second activity in any of the criteria (for proportion, $F(1,27) = 2.35$, $p = .14$; composition, $F(1,27) = 1.16$, $p = .29$; creativity, $F(1,27) = 0.35$, $p = .56$). With this result, we reject our hypothesis on the improvement of the quality of the design outcome (H2a).

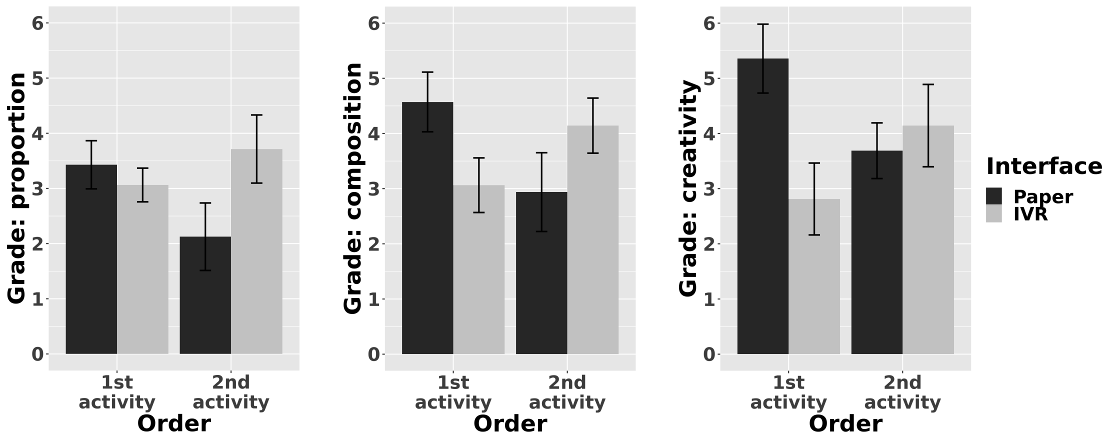

Figure 5.5 – Comparisons of grades in three criteria over time

Hypothesis H2b: Order between IVR designing and paper sketching

In order to test our hypothesis on the effect of the combination order, we analyzed the final product that the students produced after both iterations using a t-test. We observed significant effects for proportion, $t(28) = 3.91$, $p < .001$, $\eta^2 = .35$, and composition, $t(28) = 2.88$, $p < .01$, $\eta^2 = .23$, with IVR outperforming paper. We did not find a significant difference in creativity, $t(28) = 1.11$, $p = .28$. Furthermore, the differences between performing IVR first or second were significant for all three criteria (for proportion, $t(28) = 2.12$, $p < .05$; composition, $t(28) = 3.28$, $p < .01$; and creativity, $t(28) = 2.89$, $p < .01$). On the other hand, the grades from the paper sketching were lower for the second activity than the first activity for all three criteria (for proportion, $t(28) = 3.61$, $p < .01$; composition, $t(28) = 3.81$, $p < .001$; and creativity, $t(28) = 4.51$, $p < .001$). In summary, the effectiveness of IVR on the design quality was improved when it was done after the paper sketching and this ordering produced a more effective outcome for two of the three criteria supporting our hypothesis (H2b).

Hypothesis H3: Behavior in IVR

In order to investigate the effect of the behavior of learners while using the IVR application on the quality of the design outcome, we extracted and analyzed a number of process variables from the application log data. The behavior features we extracted included some time-related features such as the time spent in each mode, some design-related features such as the number of objects placed, and some simulation-related features such as how many times they simulated the designed garden. Table 5.2 shows the correlations between the behavior features and the grades in the three criteria.

From the results, we observed that the quality of the design was correlated to the percentage of the time spent in the Design mode in all three criteria when IVR was the second activity to the paper sketching (row 2) and hence negatively correlated to the percentage in the Explore mode. For the number of objects placed in the design, we observed a correlation with the

Table 5.2 – Correlations (Pearson's r) between behavior features and grades (*: $p < .05$)

Row No.	Behavior features	IVR as first activity: Proportion	IVR as first activity: Composition	IVR as first activity: Creativity	IVR as second activity: Proportion	IVR as second activity: Composition	IVR as second activity: Creativity
1	Duration total	0.169	0.024	0.029	0.038	0.209	0.230
2	Percentage Design mode	0.295	0.268	0.300	0.393*	0.409*	0.426*
3	Number of objects in design	0.046	0.207	0.119	0.248	0.455*	0.350
4	Number of mode switching	−0.159	−0.184	−0.184	0.130	0.283	0.049
5	Number of daytime change simulations	−0.380*	−0.426*	−0.470*	−0.244	−0.079	−0.044
6	Number of season change simulations	0.017	−0.188	−0.142	0.187	0.179	0.291
7	Number of year change simulations	−0.126	−0.300	−0.461*	0.149	0.264	−0.056
8	Total number of simulations	−0.232	−0.363	−0.439*	−0.059	0.032	−0.043

composition grade of the design when IVR was the second activity (row 3). When IVR was the first activity, we did not find any significant correlations for these features. On the other hand, we observed that the time-simulation-related features were negatively correlated to the design quality, particularly for creativity, when IVR was the first activity (row 5 to 8). But the correlations were not present when it was the second activity. These results partially support our hypothesis on the positive correlations with the time spent on designing and the number of objects placed, but not for the number of simulations run (H3) while the order between IVR and the paper sketching had an effect on these correlations.

We further looked into these behavior features and investigated how they are different based on whether the IVR designing was done before or after paper sketching. Figure 5.6 shows the comparison of the behavior features in the two conditions. The percentage of time spent in the Design mode was significantly higher when IVR was after paper sketching ($M = 62.0$, $SD = 19.6$) compared to before ($M = 33.6$, $SD = 11.3$), $t(28) = 4.93$, $p < .0001$. Similarly, the number of objects placed in the design was higher when IVR was after paper sketching ($M = 65.6$, $SD = 21.0$) compared to before ($M = 26.4$, $SD = 8.47$), $t(28) = 6.87$, $p < .0001$. For the total number of simulations, there was no significant difference between when IVR was after ($M = 46.2$, $SD = 22.4$) and before ($M = 58.3$, $SD = 32.4$), $t(28) = -1.17$, $p = .25$. Considering the positive correlations of the first two features to the design quality, these findings help explain why the grades were higher when the IVR designing was done after the paper sketching.

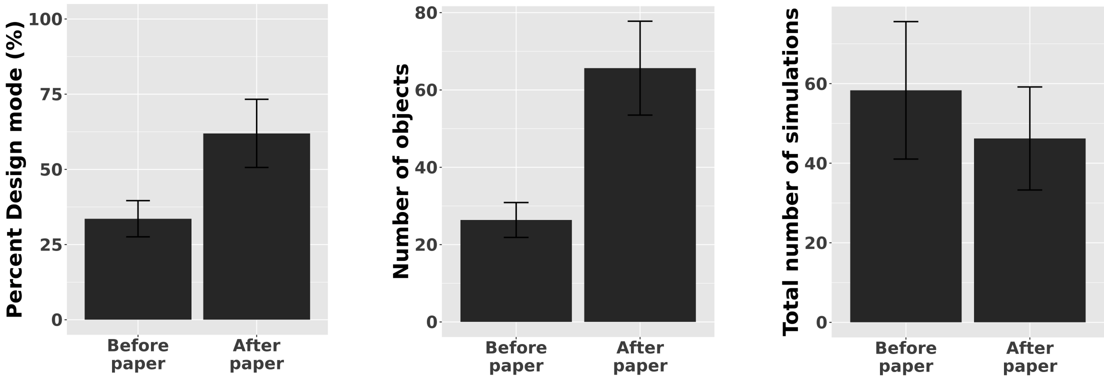

Figure 5.6 – Comparison of the behavior features from IVR in the two conditions

Hypothesis H4: Time exploration behavior

To understand better how the participants explored the time dimension, we further investigated their behavior when using the time exploration functionality of GardenVR. Our interest was on investigating whether there is a difference between the participants who produced higher-quality design outcomes and the ones with lower-quality. For this purpose, we separated the participants into two groups by the median of their average grades. The group with the higher-quality designs ($n = 14$) had the average grade of 4.26 ($SD = 0.65$) out of 7 and the group with lower-quality ($n = 16$) had 2.84 ($SD = 0.64$). We compared the two groups in two aspects: (1) in which patterns they navigated time before returning to revise the design, and (2) when they explored the time dimension in the course of the activity.

For the first point, we started with investigating how often they explored the time dimension using the three different scales (i.e., day, season, and year) before returning to the Design mode to revise the designs. The statistics are shown in Table 5.3. Both groups made a good use of the time simulation functions in all different scales before revising their designs, however, there was no statistical difference between the two groups. We also investigated if there were common patterns of exploring the different scales in the time dimension. For this, we used the n-gram algorithm [12] to extract patterns in the action sequences of the participants. Figure 5.7 shows the most common patterns of actions that led to returning to the Design mode for both groups of participants. Similar to the numbers of the time change simulations, what we observed with the patterns is that the participants did explore the time dimension using all three scales, and that there was no significant difference between the two groups.

The second approach to investigate the time exploration behavior was the temporal analysis on the time change actions, i.e., when the participants explored the time dimension in the course of the activity. For this analysis, we divided the activity time into four time bins for

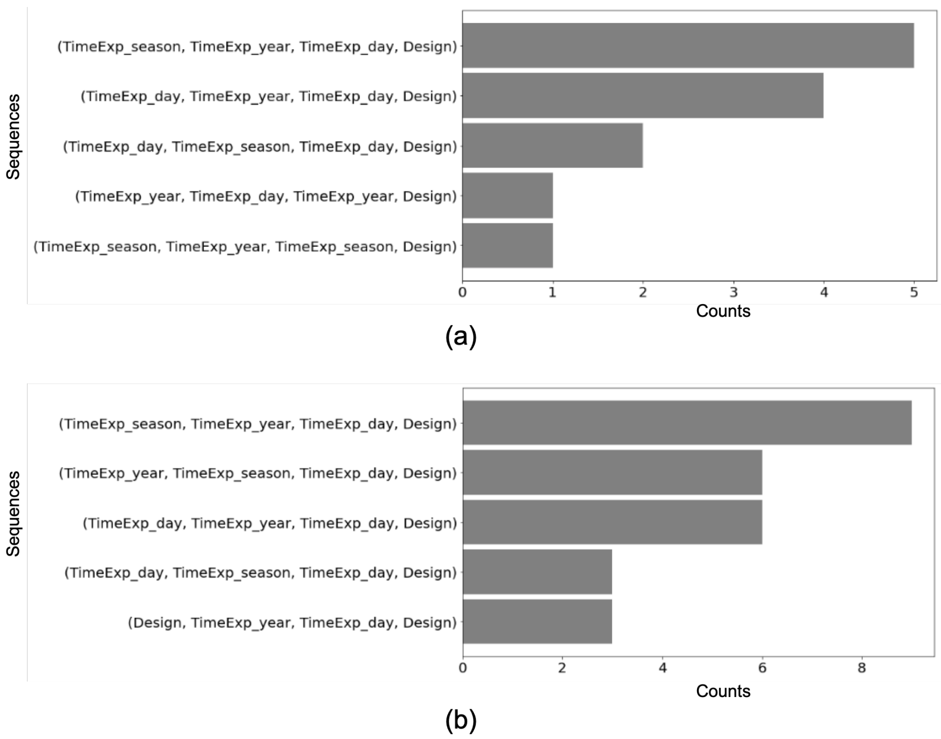

Figure 5.7 – Patterns of time exploration actions that are followed by design revision: (a) for the high-quality group and (b) the lower-quality group.

Table 5.3 – Number of time change simulations before returning to the Design mode.

	High-quality group		Low-quality group	
	Mean	SD	Mean	SD
Year change	5.10	5.32	5.19	8.31
Season change	3.61	4.47	2.51	3.78
Daytime change	1.25	1.45	1.02	1.29

each participant, and counted the time exploration actions for each bin. In this way, we can see at which stage in time the participants explored the time dimension. As shown in Figure 5.8, there was a significant difference between the high and the low groups in terms of how they explored the time in the temporal aspect. The lower groups started earlier with the time explorations during the activity compared to the higher group. The statistical difference was present in the two middle bins (for the second bin, $stat = 4.39$, $p < .05$ and for the third bin, $stat = 4.02$, $p < .05$) where the lower group did significantly more explorations compared to the higher group for both time bins. These results support our hypothesis on the behavior difference between the high-quality and the low-quality groups in the time exploration (H4).

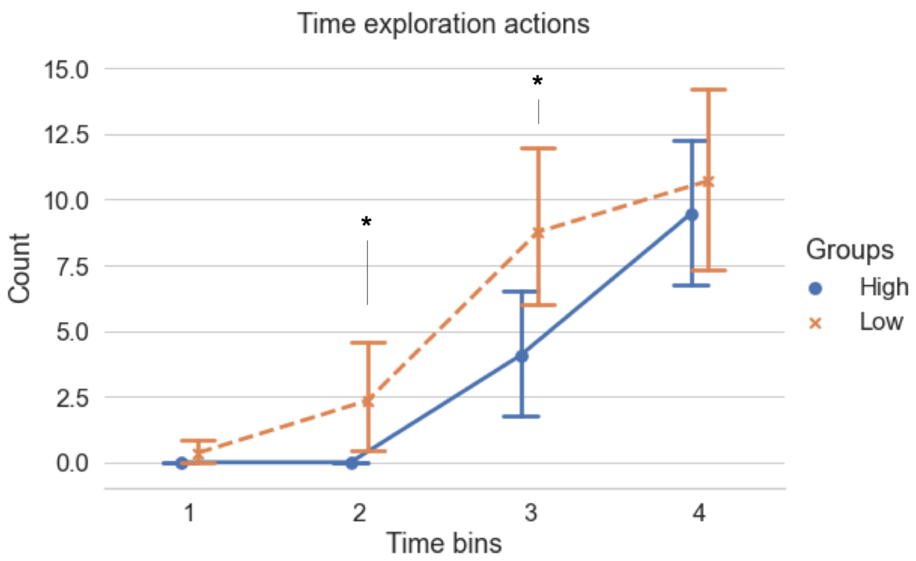

Figure 5.8 – Number of time exploration actions in time bins. The activity time is divided into four time bins for each participant and we counted the number of actions in each bin (*: $p < .05$).

5.7 Discussion

The goal of this study was to investigate the effectiveness of an IVR application in the context of VET, specifically for supporting designing skills. Using the application developed for gardener apprentices, an experimental study was conducted in order to answer four research questions on: (1) the effect of the IVR interface on the design outcome, (2) how the IVR designing can be combined with the paper sketching in order to improve the effectiveness, (3) how the behavior in the IVR application is correlated to the design quality, and (4) how the time exploration behavior is related to the design quality.

Regarding the first research question, we hypothesized a positive effect of IVR on the quality of the design outcome. In terms of overall performance, the findings from the experiment support our hypothesis in only the proportion of the design. Furthermore, in a post hoc analysis we found that this result may have been limited to only students who used the IVR after paper. One possible explanation can be that by using the IVR after having an initial sketch, the time spent in the design mode could be focused on the proportions rather than an initial design. As we see from our correlations, the time spent in the design mode when IVR is the first activity is not correlated with the proportion grade but it is in the second, supporting that having this extra time may allow students to focus on these features. However, the higher proportion score in the second IVR could be due to the learners having an opportunity to refine their designs. In this case, we would expect to see an increase in the proportion scores overall for the second activity, which we do not. Rather, the 3D representation of the design provided in IVR may support learners' designing skills in terms of the proportion, which is a spatial-related criterion [40, 73].

Further, we observed the opposite result for the creativity of the design with the paper interface being more effective. These results relate to previous work in which the immersion of VR adds more presence, but also significantly higher cognitive load and it can overload and distract the learners, resulting in less opportunity to build learning outcomes [79, 88, 120]. Interestingly, IVR did not seem to restrict creativity that was already present in a design as indicated by there being a significant difference between IVR and paper in the first designs but not the second. Students appeared to be able to carry over their creativity from their paper design as there was not a significant difference in creativity over time. Our results suggest that the increased cognitive load and the additional constraints from the interface of IVR can act as barriers against creative designs, but can be overcome by engaging in a more creative medium first [4].

For our second research question, we did not find support for our hypothesis that the students would improve their designs in the second activity. However, we did find that the combination order of the two interfaces had a significant effect on the design quality as we have begun to discuss above. For the paper sketching, the design quality was significantly lower if it was done after the IVR activity than before with the opposite effect with the IVR. One possible explanation for the decrease in the paper is that the motivation of the learners in the paper sketch as the second exercise to the IVR can be lower [41]. On the other hand, for the IVR, our results show that an appropriate preparation step before an IVR activity—a sketch on a paper in our study—can lead to an improvement of the effectiveness of IVR on the design quality.

Furthermore, in connection to our findings for the first research question, we believe that both interfaces have their own advantages and it is more meaningful to investigate how they can be combined together rather than simply comparing the two. Unlike with proportion and creativity, we did not find an overall difference in the composition scores between the paper and IVR activities. However, with further analysis, this difference may have been due to the combined ordering of the interfaces. Our results indicated in the first activity the paper interface performed better while in the second activity the IVR did. In other words, the learners that had a high composition with paper tended to keep that high composition in the IVR, and those who started with the IVR had a low composition and it stayed low when they switched to paper. One possible explanation is that the composition aspect of the design was fixated through the iterative process [136] and it emphasizes again the importance of the combination order on the design quality.

Regarding the third research question on the behavior of learners using IVR, our results show that the quality of the design outcome was positively correlated to the percentage of time spent in the Design mode and the number of objects placed in the design. These factors are related to the effort spent in designing. It is not surprising that more time and effort spent in an activity results in better outcomes. What is interesting is that the values of these behavior features were significantly higher when IVR was after the paper sketching and, therefore, the design quality was significantly better. On the other hand, we found that the number of time exploration simulations is negatively correlated to the design quality, particularly when IVR was the first activity. Although the time simulation available in IVR is one of the core features of our application, the results suggest that simulations without sufficient effort on designing are not effective as has been found in previous work around the limited effectiveness of simulations alone [34].

This finding, together with the results for the first and the second research questions, suggests that there is a benefit of performing paper-sketching before the IVR activity. Our results showed that working with a more familiar medium before doing the IVR activity was effective in producing better learning outcomes. We believe that the paper sketch created before entering the digital space helped them become more thoughtful about what they created and how they explored. This finding can be related to one of the previous studies of the Dual-T project, TinkerLamp [74], where the augmented-reality (AR) manipulatives led learners to *play* too much with them without giving enough thoughts, and they introduced a way to control for the simulations. Similarly in our study, when the learners were given the digital tool without proper guidance, they tended to explore too much without carefully thinking about it. On the other hand, when they had a preparation step with paper-sketching before entering the virtual environment, it played a role of making them more thoughtful, reducing too much manipulations, which led to a better design outcome.

Regarding the fourth research question, our investigation of the behavior in the time exploration showed that there was a temporal difference in running the time simulations between the students who produced higher-quality design outcomes and the ones did lower-quality. The lower group started with the exploration in an earlier phase during the activity whereas the higher group did most of their exploration in the second half of the activity. In combination with our findings for the third research question, our results show that it is not just about how much you explore, but what is more important is *when* you explore. One approach to study further in this direction can be to introduce control over the simulation functions by only letting the learners simulate the design once they spent enough time and effort on designing [93]. An interesting topic for future work would be to investigate the effect of reflective prompts in the application that encourage reflection during the simulations.

Although this work contributes to our understanding of using IVR to support design tasks, there are limitations to the study that should be considered and addressed in future work. First, our sample size is small. We focused on a group of students that are high in homogeneity, but small in the total number. The small sample size may impact the generalizability of our results in that it may not be representative of the general population of design-related professions. Building upon the findings of this study, we could consider two ways for the future work in order to extend it in terms of the generalizability. First, the future work could extend the study at different levels of learning within the same profession. This extension would increase the sample size but create greater differences among the students in terms of the prior knowledge, which is another factor that would need to be considered. Secondly, the future work could also consider extending the study to other professions. While the current study focused on gardener education, there are many design-related professions that could benefit from supporting the design skills and it would be interesting to investigate the cross-professional generalizability of the results.

This chapter demonstrates how an IVR tool can be designed for VET learners in design-related professions that enables them to explore the temporal dimension of a design. The focus of our experimental study was on evaluating the effectiveness of the IVR interface of the tool in supporting the learners in a designing task, while comparing it with current method of practice. Our results show that the IVR interface can be effective for the spatial-related quality of the design, but it can also act as a barrier to creative design without sufficient preparation. We also demonstrated how the effectiveness of an IVR activity can be improved when it was done as the second activity to a conventional practice. Furthermore, we showed that the time exploration of a design can be related to the quality of design outcome, and that the temporal aspect of the exploration can play an important role. The results support the potential of IVR in providing a meaningful digital experience to VET learners while emphasizing the importance of the careful design of the learning activity within and around the application.

6 Social expansion: Mixplorer

To design a digital tool that expands the experience of VET learners in the social dimension, we propose a concept of *social design space exploration* in this chapter. We developed a tool called Mixplorer that implements this concept for garden design by allowing learners to create a design and breed it with the designs of others to explore a broader space. Using the tool, we conducted two experimental studies to investigate its feasibility in the VET setting and potential benefits for the learners in design-related domains.

This chapter corresponds to the following publication:

Kim, K. G., Davis, R. L., Coppi, A., Cattaneo, A. & Dillenbourg, P. (2022). Mixplorer: Scaffolding design space exploration through genetic recombination of multiple peoples' designs to support novices' creativity. *Proceedings of SIGCHI Conference on Human Factors in Computing Systems* (accepted).

6.1 Introduction

The process of finding a solution to a creative design task often involves exploring alternative solutions created by other designers. The benefits and the drawbacks of design examples have been already introduced in Chapter 4. These alternatives provide designers with a more complete understanding of the design space [42, 35] and comparing alternatives can help them make stronger critiques and better design decisions [123, 26, 67]. Previous studies have explored different ways to support the exploration of design alternatives and shown positive effects in terms of the quality of design outcome, collaboration, and creativity support [72, 114, 135].

A particularly effective method of exploring alternative solutions is to mix and combine them to create new ideas. People can produce better ideas if they are able to learn from recombining ideas into new ideas and iterating on new ideas to improve them [14, 24, 44]. However, for a creative design task, combining, or mixing, multiple ideas to generate a new design is not a trivial process. This can be particularly challenging for the VET apprentices who are novice designers, as they can get superficially fixated on the solutions of others without being able to combine them to generate new solutions [50, 113, 112]. The ability to generate solutions to a design problem is related to the level of experience of the designers and it requires domain knowledge and expertise to maintain the quality of generated solutions [133, 76, 70].

To support novice designers with exploring and combining design alternatives we developed Mixplorer, a system to help novices generate novel designs by mixing design alternatives. The target users of Mixplorer are apprentice garden designers in VET. Mixplorer provides a simple interface that can be used to create an initial garden design and a second interface that can be used to generate alternative designs by performing a select-and-mix process. The design-mixing process of Mixplorer uses a genetic algorithm to breed two garden designs and generate a new one. However, rather than using a fitness function to select optimal designs, Mixplorer uses a "human-in-the-loop" approach. The user is provided with an interface that allows them to easily browse possible children of two designs and select the one that they prefer. This genetic exploration algorithm can be used repeatedly to generate many generations of child designs from an initial set of starting designs. Throughout this paper we use the term "design mixing" to refer to the entire process of selecting parent designs, browsing possible children, and adding children to the design space using the interface of Mixplorer. Another feature that differentiates Mixplorer from existing tools is that it enables *social* design space exploration by using designs created by peers as the initial set of designs in the mixing interface. We describe this exploration method as social because Mixplorer is meant to be used synchronously by multiple students in a classroom setting, where each student can view and mix the designs that are simultaneously being created by their peers.

To evaluate Mixplorer, we carried out two studies. First, we conducted an interview study with expert garden designers who were also instructors in the VET system to understand the potential benefits and limitations of using Mixplorer with apprentice garden designers in the classroom. The instructors reported highly-positive experiences using the application, had few reservations about incorporating it into their teaching practices, and believed that using Mixplorer would support students' divergent thinking. In the second study, we conducted a controlled experiment to compare design space exploration with design mixing to two other conditions, one with no exploration and another with random exploration. We found that design mixing with Mixplorer provided significantly more support for novices' creative practices, particularly for exploration and collaboration. We also found participants who used the design-mixing interface produced more novel designs than participants in the other two groups. Finally, we showed that making it easier for novices to explore and keep track of many ideas directly affects the novelty of the designs they produce.

6.2 Related Work

Creative thinking is defined as a cognitive ability to generate a large number of original ideas or solutions to a problem [10]. One of the barriers to creative thinking in a design task is *design fixation*, a blind adherence to a set of ideas or concepts limiting the output of design [50]. A way to overcome design fixation is to explore alternative designs in the design space. In creative work, the design outcome is not necessarily known at the outset, and designers are encouraged to first explore the space before deciding on a solution [99, 30]. However, design space exploration for a creative design problem is not a simple task, particularly for novice designers. Expert designers are more capable of generating alternative designs based on their domain knowledge and previous experience [70, 133]. On the other hand, novice designers, without the expertise and the level of experience required for this process, can benefit more from technological support for design space exploration. These creativity support tools [110] are capable of supporting novices in rapidly generating multiple design alternatives and exploring the implications of those designs.

Techniques for design space exploration can be categorized into four types: parametric exploration, history-based exploration, rule-based exploration, and genetic exploration [109]. Parametric exploration allows generating variations of a design by changing values of parameterized variables [42, 135]; systems with history-based exploration provide a mechanism to keep the history of design changes and to go back in time when needed [62]; rule-based exploration helps the designers explore related examples by suggesting them based on their designs [72, 15]; and genetic exploration involves generating new solutions by combining components of existing designs.

For the purpose of supporting designers with exploring a large volume of a design space, the genetic exploration approach is an attractive choice [109, 132]. This approach is capable of developing an initial set of starting designs into a much richer set of solutions for the users to explore [17], and has been used in 3D shape modeling [132, 95, 17], 2D graphics [122, 135], visual arts [27], architecture [32, 124], and even music [103]. However, despite the wide range of the applied domains, there are challenges and limitations in applying genetic exploration to creative design.

The first challenge is that genetic algorithms require a fitness function that evaluates the performance of a solution. For this reason, existing tools tend to be in domains where the requirements are well-specified and the performance can be measurable (i.e., engineering or architecture). For creative design, the problem is often ill-defined and it is difficult or impossible to define a fitness function that can measure the performance objectively. One solution to this problem is to involve human inputs in the loop [68, 108]. By having users perform the evaluation and selection processes, the genetic algorithm can be used for a preference-based exploration tailored to each user [109]. This is the approach we opted for in Mixplorer. Mixplorer provides a collection of novel interfaces and visualizations that are designed to support novices in (a) choosing which designs they would like to breed, (b) browsing a wide variety of possible children, and (c) selecting a child design and adding it to the set of designs that can be combined together.

However, the choice to use a human-in-the-loop instead of a fitness function gives rise to a second challenge, which is that this type of system requires a set of existing designs to be used as the source of genetic operations. For example, consider the domain of garden design. A typical genetic exploration system would not be able to support outdoor spaces which are uploaded by the user, since it would not contain any gardens designed for that space. While the system could produce random designs and use these as the initial set, the chance that any of these random designs would be judged as suitable for the space is extremely low, which would make the process of using these designs to produce children fruitless. This is not only a challenge for garden design, but for any open-ended, creative domain where each task presents a new problem with different requirements and constraints. Hence, the majority of existing systems that utilize this approach are limited to solving a generic problem (e.g., abstract 2D graphics) or a single problem (e.g., solar panel design for a specific roof) [122, 135].

We propose a solution to this problem that we call "social design space exploration." In social design space exploration, the initial set of examples used in the genetic mixing process is created by a group of designers working on the problem. Mixplorer contains a Garden Design Interface that can be used to quickly design gardens for any outdoor space, and uses a real-time, cloud-based database to collect these examples as they are created and present them to all of the users working on a common problem, where they can be used as the source designs in the genetic mixing algorithm as soon as they appear. This means that Mixplorer is not limited to a small set of designs, but can support meaningful genetic exploration on any outdoor space that a user uploads. This makes Mixplorer more than a demonstration of an exploration system, but rather a usable tool for real design tasks.

Social design space exploration may also be useful in helping novices explore a larger volume of the design space. While each individual may only be aware of a small part of the design space, collectively they can show each other parts of the space they were not considering

[111]. However, merely seeing other examples from the larger design space may not support or scaffold students in design space exploration. During the learning process, it is often not enough to provide a resource to learners; scaffolds are regularly needed to support the integration of the resource into the learning process [59, 28, 64]. Exposure to examples in a design space without a scaffolding mechanism can be similar to reading a map that shows places to visit without any streets to follow. We hypothesize that the design-mixing functionality of Mixplorer may serve as a scaffold that provides additional support for design space exploration.

6.3 Research Questions

The design of Mixplorer aims to address the challenges described above and support novice designers with exploring a broader design space for creative design. To evaluate Mixplorer, we conducted two studies where each of them tried to answer a set of research questions.

The first study was designed to learn more about the feasibility of using Mixplorer in an authentic classroom setting with VET apprentices. In particular, we were interested in answering the following questions:

- RQ1: How can Mixplorer be incorporated into design teaching and how well does it fit into the instructors' existing practices?
- RQ2: What are the potential benefits of Mixplorer for novice designers in creative practices?

The second study was built on the findings of the first study and had a more specific focus on the design-mixing functionality of Mixplorer. In particular, we were interested in learning more about the specific ways that the activity of design mixing might support novices' creative practices. We designed an experiment to answer the following research questions:

- RQ3: To what degree does the design-mixing functionality of Mixplorer support novices' creative practices during the garden design activity?
- RQ4: Do novice designers produce more novel designs after working with the design-mixing interface of Mixplorer?

6.4 Mixplorer

Mixplorer is a web application for creating a garden design and exploring the design space by mixing it with other designs. It has two phases—a design phase where users can design a new garden and an exploration phase where they can mix the designs. Users start the exploration with the design that they created in the design phase. In this section, we describe the interfaces for the two phases and explain the algorithm we developed for the design-mixing process.

Figure 6.1 – Garden Design Interface of Mixplorer

6.4.1 The Garden Design Interface

The Garden Design Interface in Mixplorer allows users to design a garden by dragging and dropping different elements into a 3D rendering of an outdoor space. In the two studies reported in this paper the outdoor space was a 3D rendering of the backyard of a Roman Catholic diocese which we reconstructed using a photogrammetry tool. We chose this site because it was an actual work site for training apprentice gardeners in a local vocational school, though in principle any 3D model of an outdoor space could be used. As shown in Figure 6.1, this interface shows the birds-eye view of the outdoor space and an inventory that includes trees, bushes, walls, benches, and stone plates. Once an item is selected from the interface, it follows the mouse and can be stamped multiple times in the garden by clicking the mouse. Items can be rotated using arrow keys on the keyboard and deleted with a right-click.

6.4.2 The Garden Exploration Interface

Once a user has created a design, they can generate and explore other designs by mixing their creation with others in the Garden Exploration Interface (Figure 6.2). Each design is represented as a node in the *Design Space Graph* on the lower left. When the mouse pointer hovers over a node, a 3D rendering of the design is visualized on the top right. In the lower center of the screen, the *Design Mixing Generator* panel is shown. After selecting two ‘parent’ designs from the Design Space Graph, users can generate child designs using Design Mixing

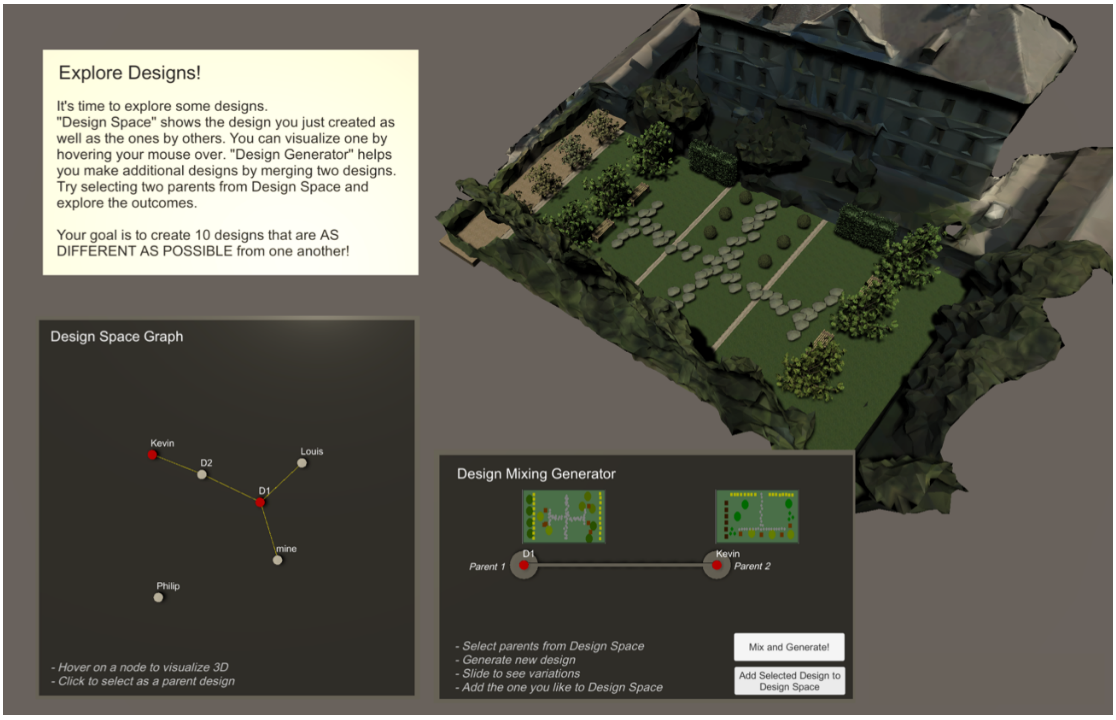

Figure 6.2 – Garden Exploration Interface of Mixplorer

Generator. This is done by moving a slider back and forth between each of the parent designs. The position of the slider affects the probability of sampling genes from one parent or the other. For example, the further the slider is placed to the left, the higher the probability that genes from the left parent will be sampled and the lower the probability that genes from the right parent will be sampled. By moving the slider back and forth, the user can quickly explore a large number of children that could be produced by the two parent designs. Once a user finds a child design that they like, they can add it to Design Space Graph where it appears as a new node and becomes available for the next iteration of mixing. Each design created in this way is visually linked to its parents using edges. As more nodes are added, the Design Space Graph tracks the history of node creation and maps which regions of the design space have and have not been explored. The process of design mixing using the Garden Exploration Interface is demonstrated in Figure 6.3.

6.4.3 Design Mixing Algorithm

We used a genetic algorithm approach to enable the ability to mix garden designs and generate multiple variations from the design space. A genetic algorithm is a meta-heuristic inspired by the biological natural selection process which is commonly used to generate solutions to search problems [130], and genetic exploration systems utilize these types of algorithms for the purpose of solution space exploration. We describe the details of our genetic algorithm used in the Garden Exploration Interface of Mixplorer in this section.

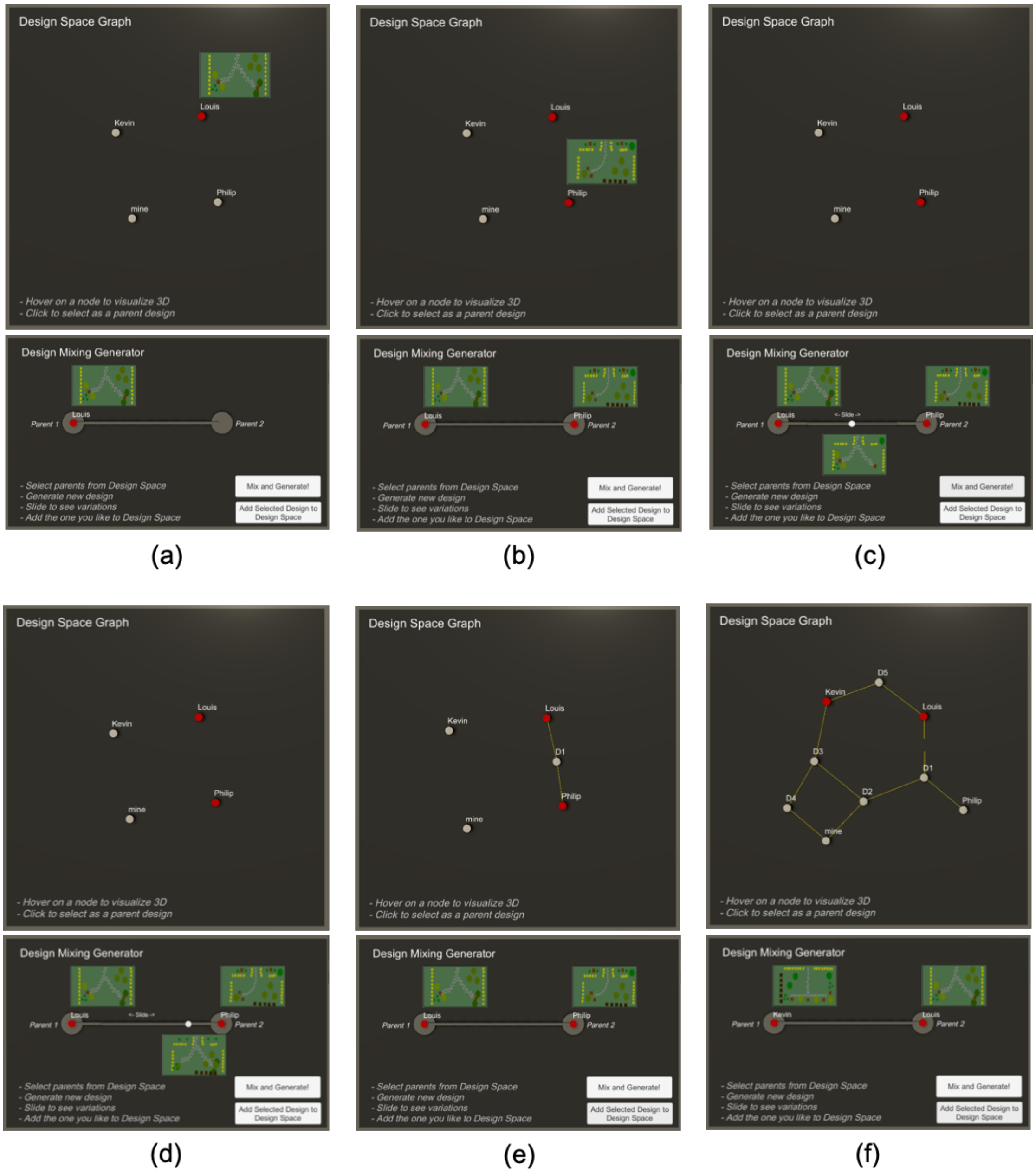

Figure 6.3 – Zoomed-in view of the Garden Exploration Interface showing the sequence of design mixing: (a) Selecting a node from Design Space Graph as the first parent, (b) selecting another node as the second parent, (c) generating children of the two parents using the Design Mixing Generator, (d) browsing different children by adjusting the slider, where the position of the slider determines the probability of inheriting features from different parents, and (e) adding a satisfactory child design to the Design Space Graph. The Design Space Graph after a few generations of children have been generated are shown in (f).

Design Representation

In order to apply the genetic algorithm to garden design generation, we needed to first define a genetic representation of a garden. When a user creates a garden using Mixplorer, the design is a set of objects that have been placed in a given space. In our genetic representation, each object, along with its position and orientation information, is called an *Item*. To capture and embed structural information of the garden, we also added another level in the representation called *Structure*. A group of Items forms a structure. Because structural information is often represented by the same type of objects (e.g., a set of bushes that form a wall or stone plates creating a path), we defined a Structure from each object type. Figure 6.4 shows an example genetic representation used in Mixplorer. Each design has all available object types as *Object Genes* in the first level. Under each Object Gene, there are a set of Structures defined by objects of that type. Finally, each Structure has a set of Items that belong to it.

```
Design 1
    ∟ Object Gene 1
        ∟ Structure 1
            ∟ Item 1: position, orientation
            ∟ Item 2: position, orientation
                ⋮
            ∟ Item n: position, orientation
        ∟ Structure 2
            ⋮
        ∟ Structure m
    ∟ Object Gene 2
        ⋮
    ∟ Object Gene k
```

Figure 6.4 – Genetic representation of a garden

Design Generation by Mixing

The process of mixing the genetic representations to produce new garden designs was performed by the genetic algorithm. A typical genetic algorithm includes the following steps: selecting items from the existing population, applying genetic operators, and applying heuristics. We describe here how each step is applied in Mixplorer.

Selection: First, a subset of an existing population must be selected to serve as 'parents' to breed a new generation. This selection process is often carried out using a fitness function that evaluates each candidate solution. However, as we have previously described, in open-ended creative domains such as garden design it can be difficult to define a function that is able to objectively evaluate a design. In Mixplorer, we adopted the 'human in the loop' approach to solve the problem [68, 108]. Instead of using a fitness function, users are asked to select candidate designs to breed. Therefore, in Mixplorer, evaluation of the designs was based on the judgment of a user, not on a pre-defined fitness function.

Genetic operators: The two main genetic operators used in the genetic algorithm were crossover and mutation. Crossover operators combine the genes of the parents to produce a child and mutation operators alter gene values to maintain diversity. We defined three types of crossover operators for Mixplorer:

- Tree vs. non-trees crossover: A child takes the tree genes from one parent and non-tree genes from another. This is the crossover at the highest level.
- Gene-level crossover: A child takes the Object Gene of each object type from one of the parents. This is a standard way of doing a crossover.
- Structure-level crossover: Each Structure from a parent can be inherited to one of its children. As a result, one Object Gene can have more than one Structure.

For mutation, we defined four types as follows:

- Change type: A Structure of an Object Gene is transferred to another Object Gene.
- Switch type: Two Structures from two Object Genes are swapped.
- Mirror: All objects are mirrored around the vertical or horizontal axis.
- Mirror half: A random half of the design is selected, copied, and mirrored to the other side.

Each type of crossover and mutation was applied with an equal probability in the mixing process.

Heuristics

In genetic algorithms heuristics are often introduced to make the process more robust. In Mixplorer, we added two heuristics to validate the designs generated by applying the genetic operators:

- If an added Structure is superposed onto another Structure, undo the addition.
- If a generated child design is too similar to one of its parents, ignore the child.

Figure 6.5 shows example designs generated using the design mixing process described above.

6.5 Study 1: Interviews with Expert Garden Design Instructors

Based on our previous experiences working with garden-design instructors, we knew that Mixplorer was unlike other tools being used in the garden design curriculum [58]. This meant

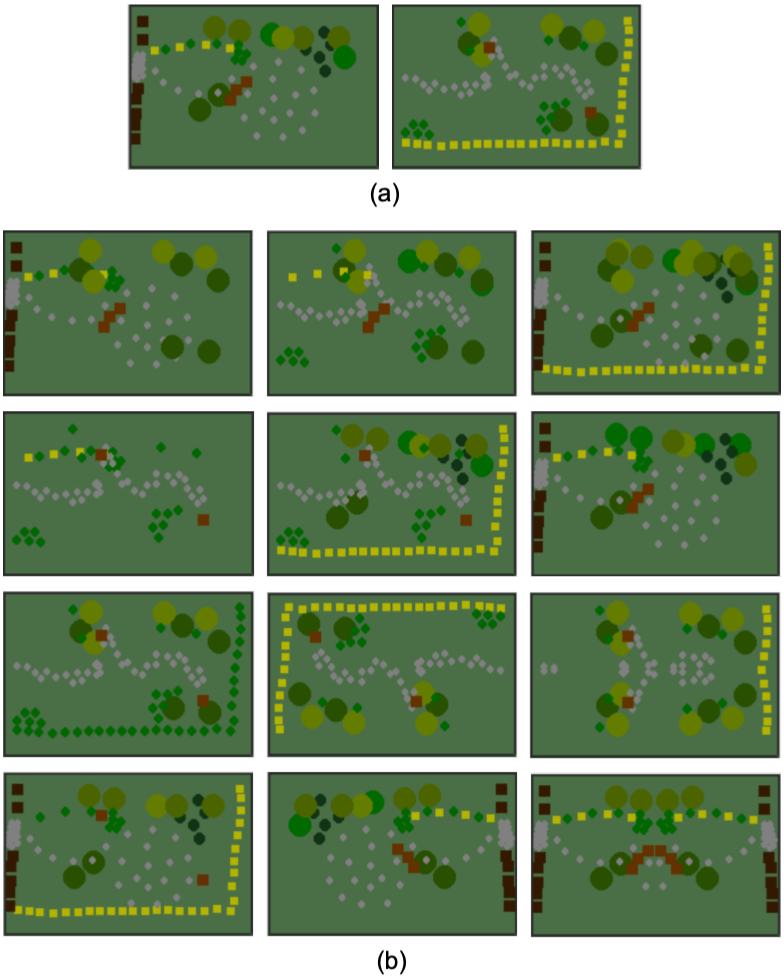

Figure 6.5 – Example designs generated using the mixing process of Mixplorer: (a) parent designs and (b) child designs generated using different genetic operators

there was a valid threat of Mixplorer not being adopted by instructors because of being too novel or foreign to their current practices. To address this concern, we recruited six garden design instructors from vocational schools to take part in a semi-structured, task-based interview with the Mixplorer application. The first goal of this interview was to learn more about the feasibility of using Mixplorer in an authentic educational setting with apprentice designers. In particular, we were interested in understanding whether instructors would incorporate Mixplorer into their teaching, and if so, how they saw it fitting into their existing practices. The second goal of the interview was to see whether instructors believed that Mixplorer could be used to support their students' divergent thinking, and if so, how much of this support could be attributed to the design-mixing functionality.

6.5.1 Methods

Participants

We recruited six garden design instructors from vocational training schools the Ticino region of Switzerland. The average age of the instructors was 48 years ($SD = 10.28$). The instructors had a combined 83 years of teaching experience, and as a group were currently responsible for teaching over 400 apprentices per year.

Procedure

Instructors were interviewed one-at-a-time using the Zoom videoconferencing platform, and audio, video, and screen recordings of each interview were recorded using the built-in capabilities of Zoom. After a short introduction to the study which included filling out a consent form, instructors were provided with a web link to Mixplorer and asked to open the website on their browser.

Once the application was loaded, the instructors were guided through three phases of using the application. In the first phase, the instructors were given the Garden Design Interface of Mixplorer and prompted to "design a garden for the backyard of a Roman Catholic Diocese, [where the] goal is to create a space for the residents and visitors to rest or take a short walk." The interface contained an inventory of garden design elements such as trees, bushes, stones, and benches which could be dragged and placed into a three-dimensional model of the backyard of the Diocese (Figure 6.1).

After completing their design, the instructors moved onto the second, design exploration phase. In this phase, they were presented with the Garden Exploration Interface of Mixplorer for mixing and exploring garden designs. They were asked to use the interface to "generate new designs that are as different as possible from one another." Once they were satisfied with their designs, they moved on to the third and final phase.

In this third phase, the instructors were first presented with all of the designs from the second phase and asked to choose the three designs they liked most. After selecting three designs, they were brought back to the design interface from the first phase. With the three selected designs displayed at the top of the screen, the instructors were asked to re-design the garden for the Catholic Diocese. Once they were satisfied with their design, they exited the application.

Instructors were then asked questions from a semi-structured interview protocol which is described in the next section. After answering the questions, the instructors were given a link to an online version of the Creativity Support Index [16] and asked to spend a few minutes filling it out. Finally, the instructors were thanked for their participation and the interview ended.

Interview Protocol

The semi-structured interview protocol covered four topics: experience using the application, instructors' thoughts about how they might use Mixplorer in the classroom, instructors' beliefs about the importance of divergent thinking in garden design, and the instructors' beliefs about how Mixplorer might support students' divergent thinking skills. The full interview protocol is provided in our supplementary materials.

6.5.2 Results

Experience Using the Application

Overall, the instructors reported highly-positive experiences using the Mixplorer application. Regarding usability, five of the six of the instructors said that the application was intuitive and easy to use. One instructor commented that "Compared to [other applications] that I've tried in the past I found it very easy and responsive." Another said that "It is very simple. Although I was skeptical at first, it's very easy to understand." A third said "For someone like me who doesn't use a computer it becomes really easy and sharable." When asked about whether he enjoyed using the application, the lone instructor with doubts about its usability said "It's difficult to say... I'm better at drawing on paper," though he later admitted that the application "seems very intuitive and easy."

An analysis of the application logs confirmed that all of the instructors were able to use the full functionality of the Garden Exploration Interface without issue. The action sequences of each instructor are shown in Figure 6.6. On average, each instructor initiated the design-mixing process 5.83 times ($SD = 1.33$) and interacted with the slider to explore design variations 15.5 times ($SD = 7.34$). After exploring the possible children, each instructor added an average of 4.67 designs to their Design Space Graph ($SD = 1.21$).

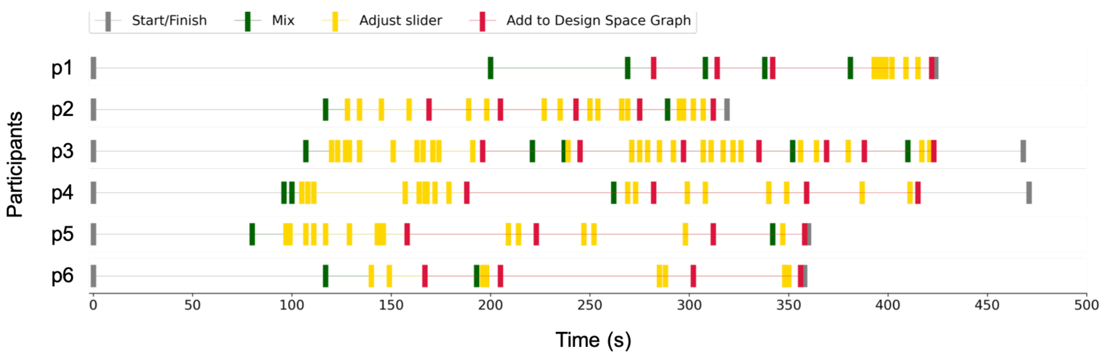

Figure 6.6 – Action sequences of the instructors in the exploration phase from Study 1

Feasibility of Using Mixplorer in the Classroom

All of the instructors were open to using Mixplorer with their students, and most were enthusiastic about its potential. One instructor commented "I'd really like to try it with the apprentices," and another said "I put myself into the shoes of the pupils who, after explanation and testing, I'm sure will be able to use it to great effect." Most felt that the tool was appropriate for novices (i.e., first-year apprentices). However, one instructor expressed doubts about whether Mixplorer could be used by true novices, saying "I think it's a more suitable tool in the third year where you can already open up a little bit to the students and show them what they can do after the certificate at a professional level."

This openness to using the tool was somewhat surprising because of our original assumptions. As previously mentioned, one of our concerns about Mixplorer was that it would be too different from the tools that instructors were currently using in their teaching. The instructors confirmed that this was the case. One said "I have never seen a similar application that had this functionality," and another said "It's definitely an interesting tool and it's not the usual piece of paper that is typically used while drawing." However, these differences were generally seen as a good thing: not as reasons to avoid using the tool, but as improvements over existing tools and methods. Mixplorer was perceived as fitting into instructors' current practices better than other software tools, which were described as overly complex and difficult to use. One said "In general, [other] applications get complex before they got to a stage like this with a rendering, and for people like me who are not architects [these other tools] are difficult." In contrast, Mixplorer was perceived as less complex and easier to use. One instructor commented that "Compared to [other applications] that I've tried in the past I found it very easy and responsive."

Though the instructors were not asked specifically about Mixplorer's potential for supporting collaboration, four of the six instructors spontaneously mentioned this as a reason to use the tool. These instructors explained how collaborating on design problems often resulted in better solutions, and liked how Mixplorer offered a means for students to "work with two heads and two ideas." Unexpectedly, multiple instructors described a way of using Mixplorer to support collaboration that we had not considered: Mixplorer could help multiple people, each with their own solution to a design problem, converge on a single satisfactory solution. One said "At some point we can take the groups' projects and put them together and see, by mixing ideas, what comes out. Surely, with these four ideas mixed together, you come up with one that is very similar, acceptable to everyone and also easily achievable." Another that "It could help having the design coming from different designers since, I think, it's more useful because you can take the best things from different drawings." Two instructors felt that Mixplorer could also be used in professional settings as a way to support collaboration between professional designers and clients. One explained how the application might help reconcile the work of multiple landscape architects, describing a situation where he had worked with "a more practical and a more theoretical collaborator." Another hypothesized that "It could be interesting to do in the profession with the gardener mixing and then showing it to the client or ask the client to mix and the discuss possible changes."

Supporting Students' Divergent Thinking Skills with Mixplorer

Four of the six instructors believed that the design-mixing functionality of Mixplorer would support divergent thinking. One instructor said "the mixing of two projects was useful because it made me see a situation I hadn't planned... From a technical point of view, the scenario with the mix [when compared to simply seeing other examples] gives more insights. Apprentices who do not have an overview because they lack experience could benefit... The divergence between the projects and the mixing certainly opens up different visions than what was planned at the beginning with the first design." Another echoes this sentiment, saying "I find [design mixing] very creative as a function and it can also help to open the minds of those who may be struggling a little more. It can help to visualize and get out of the box but then it also depends on the apprentice."

However, two instructors raised doubts about the value of design mixing. One felt that it was enough to present novel examples to apprentices, and that the mixing part of the application was unnecessary. This instructor said "Surely seeing the other design is helpful but I don't know about mixing... The idea of showing the drawings of one's classmates is a good one, while I don't know about mixing." The other instructor with doubts felt that the design mixing functionality did too much of the work for the apprentice, saying "Of course seeing all the designs and then having the apprentice manually mix [could] be more interesting. In this case the apprentice is the one who has to actively work, instead of here [where the system does the mixing]."

6.5.3 Discussion

The interviews with garden-design instructors gave us more confidence about the feasibility of using Mixplorer in the classroom with apprentices. Our concerns about Mixplorer being too foreign to instructors current teaching practices were largely unfounded. All of the instructors reported that Mixplorer was intuitive and easy to use, and all were open to incorporating it into their courses. Not only did most instructors feel that Mixplorer would be able to support students' divergent thinking, but they also suggested using Mixplorer as a collaborative design tool, which was a use that we had not considered. However, two of the instructors raised doubts about the value of the design-mixing functionality of Mixplorer. One felt that the design-mixing algorithm was doing too much of the work, and that students would benefit more from manually mixing the example designs. Another felt that design mixing was unnecessary, and that it would provide no additional benefits over simply showing students each others' designs. Given their many years of experience we took these instructors' doubts seriously, and designed Study 2 to more closely investigate the value of design mixing as a method for supporting novices' creative practices.

6.6 Study 2: A Controlled Experiment to Assess the Value of Design Mixing

Motivated by the results of the first study, the second study was designed to more closely investigate the effect of the design-mixing process of Mixplorer. Through a controlled experiment with novice designers, we compared the design-mixing functionality with two other conditions—a baseline condition with no exploration and another condition who could explore the design space by generating random examples. By comparing these groups, it was possible to determine whether design-mixing provided extra support for novices' creative practices, or whether it was no better than simply providing examples.

6.6.1 Methods

Participants

We recruited 66 paid participants (47 female and 17 male) on the Prolific recruiting platform [90] aged between 18 and 35 years ($M = 21.59$, $SD = 3.54$). The majority of the participants were students (63 students, 3 non-student), and we excluded art and design majors in the study as the target users of Mixplorer were people without any prior design experience. The reason why we conducted the experiment with online participants instead of VET apprentices was the limited access to VET schools during the pandemic.

Experimental Design

In order to study the effect of exploring the design space using Mixplorer, we designed a between-subjects experiment with three conditions: (1) no exploration, (2) random exploration, and (3) mixing exploration. Each participant was randomly assigned to one of the three conditions for the exploration activity. The first condition served as a baseline for the comparison. To further investigate the effect of the process of mixing in design exploration, we added the second condition where the participants were provided with randomly generated designs. Participants in this condition could see a new design in the design space simply by clicking a button rather than performing the select-and-mix process of Mixplorer. The random designs were generated using the same algorithm used for mixing but with two randomly selected parents, but the relationship between the designs in the space was not visualized (i.e., no lines connecting the design nodes). And in the third condition, we provided the full functionality of Mixplorer.

Task and Materials

In the first phase of the study, participants in all three groups used the Garden Design Interface of Mixplorer to design a garden for the backyard of a Roman Catholic Diocese. In the second phase of the study, each group used a different version of the Garden Exploration Interface.

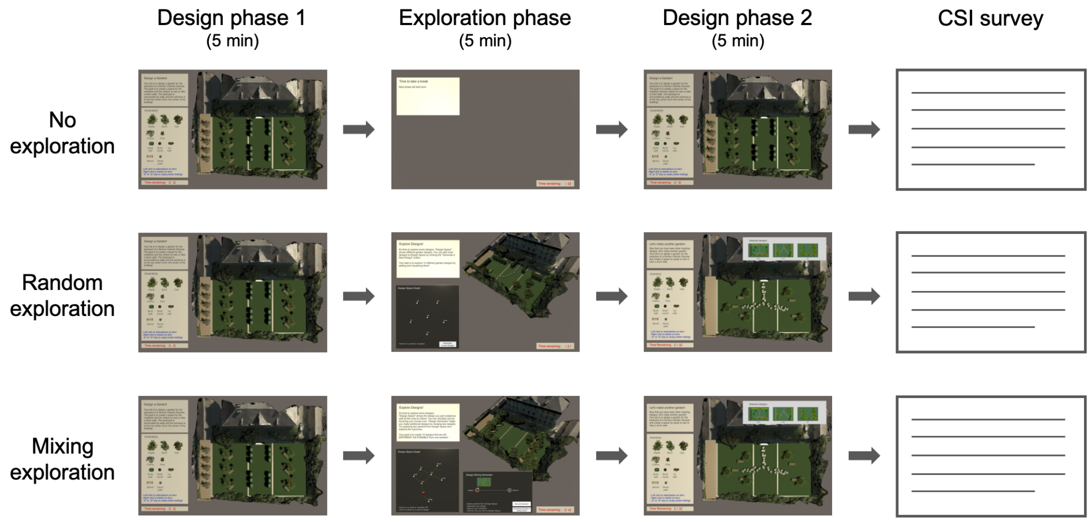

Figure 6.7 – Experimental design of Study 2: The experiment was composed of three phases followed by the CSI survey. Each phase was controlled for time. Different exploration interface was provided for each condition as shown. For the random and mixing conditions, the participants had three designs chosen from the exploration phase displayed in the final design phase.

The mixing-exploration group used the complete interface with the Design Space Graph and Design Mixing Generator. The random-exploration group was given a modified version of the Design Space Graph which did not show edges between nodes, and in place of the Design Mixing Generator they had a button which would generate random designs. The no-exploration group did not see any version of the Design Space Graph or Design Mixing Generator, and instead saw a message asking them to wait for the next step.

For the exploration phase of the experiment, participants in the mixing-exploration and random-exploration groups were provided with an initial set of three designs different from their own design. For this purpose, we selected three designs that were created by the expert garden designers in the first study. We chose the three designs that were most visibly different from one another so that participants mixing these designs would produce a wider variety of outcomes from the full design space.

Procedure

At the beginning of the experiment, the participants were provided with a description of the study and asked to fill out a digital consent form if they wished to participate. Afterwards, they were given a tutorial on how to use the Garden Design Interface of Mixplorer. We provided the description of the task and the inventory of the available objects described above. Once the participants were ready, they were given five minutes to complete the task using the Garden Design Interface.

After finishing their initial design the participants moved on to the exploration phase of the study. Participants in the mixing-exploration condition and random-exploration condition were given five minutes to generate 10 new designs using their respective interfaces, while participants in the no-exploration condition were asked to wait for the next phase.

After completing the exploration phase, the participants in the mixing-exploration and random-exploration conditions were presented with all of the designs that they generated in the exploration phase and asked to choose their three favorites. After selecting three designs, they moved to the third phase of the study where they were given a second chance to design a garden using the Garden Design Interface. During this phase their three favorite designs were displayed at the top of the screen for reference. After five minutes, the participants were asked to complete the Creativity Support Index based on their experience with the application and the study concluded.

Measures

The Creativity Support Index (CSI) is a standardized psychometric tool that evaluates the creativity support of a system [16]. The CSI provides quantitative assessments in six dimensions of creativity support: Enjoyment, Exploration, Expressiveness, Immersion, and Results Worth Effort. Each participant was asked to fill out the CSI survey after the second design activity. The CSI made it possible to evaluate how different design-exploration functionalities supported the users' creative work.

We were also interested in understanding how using the different functionalities affected the participants' ability to produce novel designs. We operationalized novelty by comparing each participant's initial design (created before using any of the three exploration interfaces) to the design they created after working with the interface. By comparing the difference between the designs created before and after the exploration phase, we aimed to show quantitatively how much the design outcome was influenced by the different exploration methods. Again inspired by genetics, we used Levenshtein edit distance [75, 86] to quantify the difference between genetic representations of each participant's initial and final designs. We used the magnitude of the edit distance as a proxy for novelty, where large edit distances indicated that the second design was more novel, and smaller edit distances indicated that the second design was less novel.

6.6.2 Results

Creativity Support Index

We found a significant difference among the three conditions on the overall CSI score ($F(2,63) = 4.53$, $p < .05$). Post-hoc comparisons showed that the CSI score of the mixing-exploration condition ($M = 73.59$, $SD = 15.01$) was significantly higher than the no-exploration condition ($M = 55.90$, $SD = 26.24$), $t(41) = 2.79$, $p < .01$. The score of random exploration ($M = 68.52$,

Table 6.1 – The CSI factor scores for the three conditions, Mean (SD).

	No exploration	Random exploration	Mixing exploration
Enjoyment	10.7 (5.91)	13.6 (3.50)	14.8 (4.00)
Exploration	10.8 (5.44)	13.1 (3.58)	15.3 (2.62)
Expressiveness	12.4 (5.53)	13.7 (4.08)	14.6 (3.61)
Collaboration	7.39 (4.82)	11.2 (4.41)	14.0 (3.45)
Immersion	11.6 (4.90)	14.4 (3.58)	13.4 (4.84)
Results worth effort	11.2 (5.48)	14.0 (3.73)	14.6 (4.04)
Overall CSI score	55.90 (26.24)	68.52 (17.57)	73.59 (15.01)

Table 6.2 – CSI factor counts for the three conditions, Mean (SD).

	No exploration	Random exploration	Mixing exploration
Enjoyment	2.61 (1.31)	2.29 (1.23)	2.27 (1.67)
Exploration	3.57 (0.90)	4.05 (1.20)	3.50 (1.26)
Expressiveness	3.00 (1.35)	2.76 (1.22)	3.05 (0.95)
Collaboration	0.30 (0.47)	0.62 (1.16)	1.00 (1.23)
Immersion	1.91 (1.35)	1.95 (1.32)	1.95 (1.36)
Results worth effort	3.61 (1.41)	3.33 (1.28)	3.23 (1.31)

$SD = 17.57$) was not significantly different from either no exploration, $t(41) = 1.89$, $p = .066$, or mixing exploration, $t(41) = 1.01$, $p = .32$ (See Table 6.1 and 6.2).

We performed a statistical comparison between the three conditions on the six scales of CSI and found statistically significant differences in four criteria: Enjoyment, $F(2,63) = 4.60$, $p < .05$, Exploration, $F(2,63) = 6.66$, $p < .01$, Collaboration, $F(2,63) = 13.6$, $p < .001$, and Results Worth Effort, $F(2,63) = 3.73$, $p < .05$. We did not find a significant difference for Expressiveness, $F(2,63) = 1.31$, $p = .28$, and Immersion, $F(2,63) = 2.24$, $p = .11$. Figure 6.8 shows the comparisons of the six factor scores across the three conditions.

We performed post-hoc comparisons on each of the four factors to better understand the differences between conditions. On the Exploration scale, the mixing-exploration group ($M = 15.3$, $SD = 2.62$) scored significantly higher than both no-exploration ($M = 10.8$, $SD = 5.44$), $t(41) = 3.52$, $p < .01$, and random-exploration ($M = 13.1$, $SD = 3.58$), $t(41) = 2.22$, $p < .05$. The difference between the random-exploration and no-exploration groups was not significant, $t(41) = 1.68$, $p = .10$.

On the Collaboration scale, the mixing-exploration group ($M = 14.0$, $SD = 3.45$) was significantly higher than both no-exploration ($M = 7.39$, $SD = 4.82$), $t(41) = 5.30$, $p < .001$, and the random-exploration ($M = 11.2$, $SD = 4.41$), $t(41) = 2.28$, $p < .05$. The random-exploration group also scored significantly higher than no-exploration, $t(41) = 2.76$, $p < .01$.

On the Enjoyment scale, the mixing-exploration group ($M = 14.8$, $SD = 4.00$) scored significantly higher than the no-exploration group ($M = 10.7$, $SD = 5.91$), $t(41) = 2.72$, $p < .01$, but did

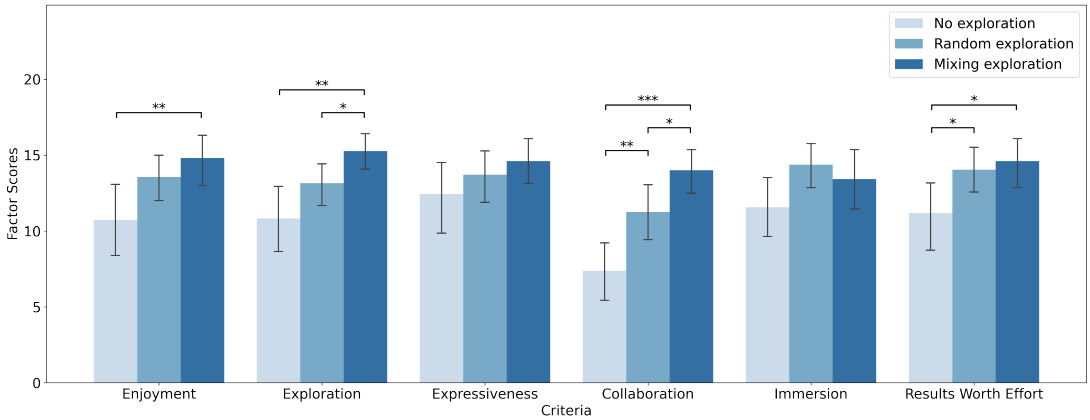

Figure 6.8 – Comparison of CSI factor scores (*: $p < .05$, **: $p < .01$, ***: $p < .001$)

not score higher than the random-exploration group ($M = 13.6$, $SD = 3.50$), $t(41) = 1.09$, $p = .28$. Finally, on the Results-Worth-Effort scale, the mixing-exploration group ($M = 14.6$, $SD = 4.04$) scored significantly higher than the no-exploration group ($M = 11.2$, $SD = 5.48$), $t(41) = 2.39$, $p < .05$, but did not score higher than the random-exploration group ($M = 14.0$, $SD = 3.73$), $t(41) = 0.458$, $p = .65$.

Novelty of Design Outcomes

The difference between each of the participant's initial and final designs was computed using Levenshtein edit distance. We used this difference as a proxy for novelty, where a large difference between the two designs was considered more novel than a smaller difference. We found that the mixing-exploration group ($M = 164.4$, $SD = 47.6$) produced significantly more-novel designs than the no-exploration group ($M = 128.0$, $SD = 47.0$), $t(41) = 2.55$, $p < .05$. However, the mixing-exploration group's designs were not significantly more novel than the random-exploration group ($M = 151.3$, $SD = 54.4$), $t(41) = 0.84$, $p = .41$, and the random-exploration group's designs were not significantly more novel than the no-exploration group's designs, $t(41) = 1.50$, $p = .14$. The results are shown in Figure 6.9.

Use of Mixing Interface

To understand better how the design-mixing functionality was used, we investigated how the participants in the mixing condition ($n = 22$) interacted with the interface. The average number of mixing performed by each participant was 23.2 ($SD = 14.5$) and they interacted with the slider to explore design variations 29.9 times in average ($SD = 32.7$). Both measures had large standard deviations showing an evidence that they have used different ways to explore the generated designs. After exploring the variations using mixing and adjusting, the participants added 11.2 designs to their Design Space Graph in average ($SD = 4.37$). The action sequences are shown in Figure 6.10.

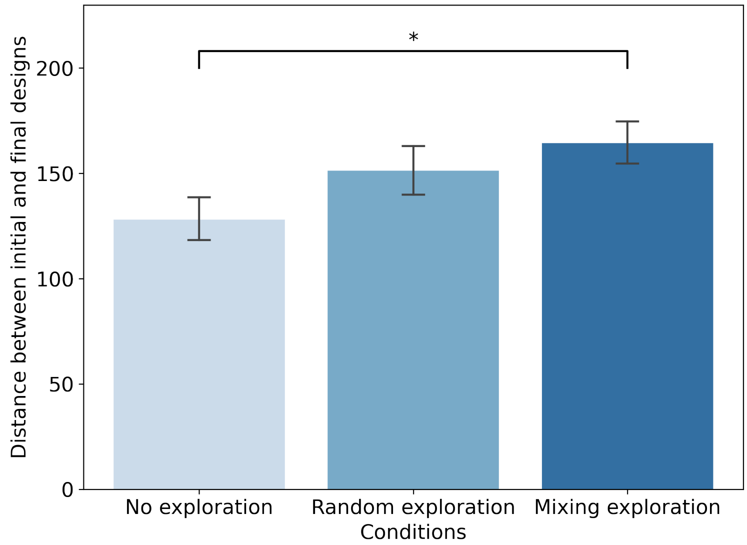

Figure 6.9 – Comparison of the edit distance between initial and final designs. The error bars show standard errors (*: $p < .05$)

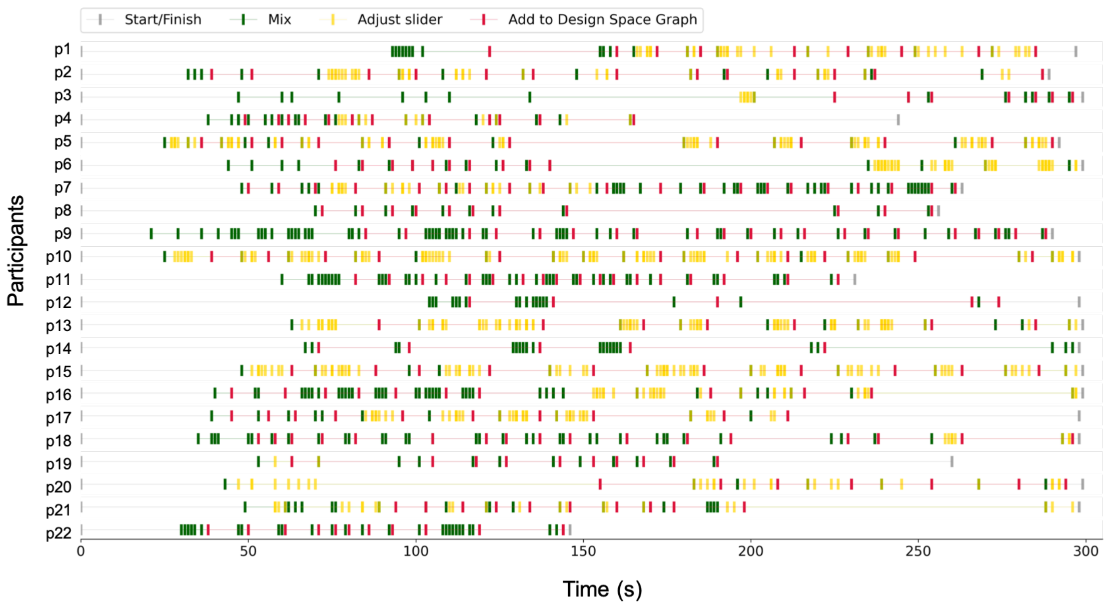

Figure 6.10 – Action sequences of the participants using design mixing in Study 2

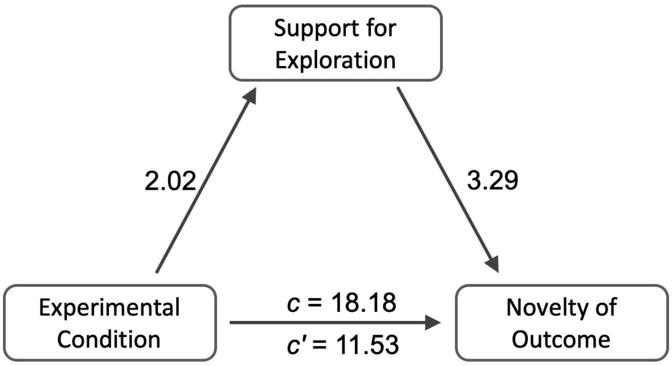

Figure 6.11 – Support for Exploration (CSI) fully mediated the relationship between the experimental condition and the novelty of the outcome. The total effect (c) of Experimental Condition on Novelty of Outcome was 18.18, $SE = 7.45$, $t(63) = 2.44$, $p = 0.017$. The direct effect (c') of Experimental Condition on Novelty of Outcome after removing Support for Exploration was 11.53, $SE = 7.89$, $t(62) = 1.46$, $p = 0.15$. The mean bootstrapped indirect effect (ab) of Experimental Condition on Novelty of Outcome through Support for Exploration was 6.67 with $SE = 3.27$, $C.I.(1.34, 14)$, $R = 0.39$, $R2 = 0.15$, $F(2, 62) = 5.43$, $p = 0.0022$.

Mediation Analysis Connecting Support for Exploration with Novelty of Outcome

We performed a simple mediation analysis where the outcome variable was novelty of design outcome, the mediator variable was support for exploration from the CSI measure, and the independent variable was the experimental condition. The indirect effect of experimental condition on the novelty of the design outcome was statistically significant (effect=6.67, 95% C.I. (1.34,14), $p < 0.01$). More details can be found in Figure 6.11.

6.6.3 Discussion

Study 2 was designed to investigate the creativity support of the design-mixing functionality for novice designers and its impact on the novelty of the design outcome. Our results showed that design mixing provided significantly better support for novices' creative activities, particularly for the Exploration and Collaboration factors. Additionally, we found that the participants were able to produce designs that were more different from their initial designs after using the design-mixing functionality. Finally, a mediation analysis allowed us to connect these findings and show that making it easier for novices to explore and keep track of different ideas directly affects the novelty of the designs they produce.

Design Mixing with Mixplorer Supports Novices' Creative Practices

Recall that two of the instructors in Study 1 raised doubts about whether the full functionality of the Garden Exploration Interface was necessary to support students' creative practices. This was the main inspiration for Study 2, which was designed to determine whether the full design-mixing functionality of Mixplorer provided added value over (a) nothing and (b) simply showing novices examples. By using the CSI we were able to break up the construct of "support for creative practices" into six sub-scales. We found that Mixplorer was better than the baseline condition on four of the six sub-scales: Enjoyment, Exploration, Collaboration, and Results Worth Effort. These results showed that the full design-mixing functionality of Mixplorer provided robust support for novices' creative practices (i.e., that it was better than nothing).

However, these results could not answer the question about whether this was due to engaging in the design-mixing activity, or if it was due to simply seeing the new examples generated by design-mixing. This question could only be answered by comparing the mixing-exploration and random-exploration groups. We found that the full design-mixing functionality of Mixplorer provided significantly better support than the random-exploration condition on two of the scales: Exploration and Collaboration. This meant that (a) the full Garden Exploration Interface made it easier to explore and keep track of many different ideas or designs than an example-only interface, and (b) the full Garden Exploration Interface was felt to be better for sharing ideas with others and for working together with others. This second result is likely to be related to the comments from the instructors in Study 1 regarding the potential use of Mixplorer as a collaboration tool among multiple designers. Together, these findings tell us that design mixing *does* provide added value over simply showing students examples. Furthermore, this additional support happens to be along the two most-relevant dimensions of the scale, since Mixplorer was specifically designed for *social* design space *exploration*.

Novices Create More Novel Designs After Using Mixplorer

In the first set of results we found that novices reported that Mixplorer provided extra support for creative practices. We were also interested in seeing whether this additional support would have an effect on the design outcome. As discussed previously, one of our hypotheses was that the support provided by Mixplorer would translate into more novel designs. where novelty was evaluated by comparing each participant's second design to their initial design. We found that the final designs created by the participants in the mixing-exploration condition were significantly more novel than those created by participants in the no-exploration condition. And as shown in Figure 6.9, the novelty of the random-exploration condition was between the other two conditions, although the difference was not significant. These findings indicated that the design-mixing interface of Mixplorer provided support that resulted in the creation of more novel designs.

Exploration Support Fully Mediates the Relationship Between Interface Used and Novelty of Final Designs

In order to better understand why the mixing-exploration group produced more novel designs than the other two groups we conducted a simple mediation analysis (Figure 6.11) where the experimental condition was the independent variable, the novelty of the outcome was the dependent variable, and the Exploration score of CSI was the mediating variable. We found that Support for Exploration fully mediated the relationship between experimental condition and novelty of outcome. In other words, making it easier for novices to explore and keep track of different ideas directly affects the novelty of the designs that they produce. This result confirmed that participants in the mixing-exploration group produced more novel designs than participants in the other groups because Mixplorer provided better support for creative exploration.

6.7 Overall Discussion

Taken together, the results of the two studies showed the benefits of design mixing in Mixplorer for design space exploration and the potential usefulness for novice designers. The results from our interviews with instructors showed the feasibility and potential benefits of using Mixplorer in an educational setting, however, it also raised some questions about the value of design mixing for novices. The results of the second study helped answer these questions. In this study, we found that design mixing supports exploration and collaboration and supports designers in making more novel designs.

Mixplorer has been designed to be used with VET apprentices in an educational setting. However, it remains to be seen whether the positive results reported here will translate to students in a classroom setting. As the situation with the pandemic forced us to conduct an online study with non-VET participants, it is a logical next step to conduct a follow-up study with garden-design apprentices in a VET institution. In addition to replicating results reported here, this follow-up study could also investigate the effect of using one's peers' designs as the initial set of designs in the Garden Exploration Interface. Moreover, it would be valuable to investigate how Mixplorer could function as a collaboration tool to help multiple designers converge on a common solution to a design problem.

Another open question has to do with the effects of design mixing on subsequent designs. Although our work shows that the design-mixing process helped the participants generate more novel designs, it has nothing to say about the quality of these designs. For an ill-defined problem such as garden design, it is difficult to define an objective measure that can evaluate a solution. Answering this question would require an expert evaluation of the designs. In a classroom scenario, this would be feasible as it would be natural for the instructors to give feedback on the apprentices' designs and evaluate their quality.

One issue raised by a number of instructors from the first study was whether the tool is doing the job for the apprentices. Particularly from a constructivist viewpoint, the process of mixing is better to be done by the apprentices, instead of the algorithm, in order to maximize learning. It is a valid argument that needs further investigation in follow-up studies. Although we showed the effectiveness of the design-mixing functionality of the tool, we did not compare it with the manual mixing done by the apprentices. We still see an advantage of the algorithm-driven mixing of Mixplorer in terms of allowing the learners to get exposed to a large number of design variations as the manual mixing is very slow and demanding, and the learners might not be able to see the social value in the process. Moreover, the availability of the algorithm-driven mixing functionality can allow for more options for instructional design. For instance, instructors can design a lesson where the use of the tool and the manual mixing activity can be combined together in order to benefit from both.

We focused on garden design as the target domain, but we can anticipate the extendability of Mixplorer to other design domains. If the designs in the domain contain different types of objects that are arranged in two-dimensional spaces and some degree of symmetry is considered pleasing (e.g., interior designs or texture pattern designs), then the method used by Mixplorer should work without modification. For other domains, what is required in order to use the Mixplorer methods is to come up with new ways of genetically representing the designs tailored to the domains [17, 95, 103], but the general idea of social design-space exploration certainly applies across a wide range of design domains.

In this chapter, we explored the social dimension for designing a digital tool that can provide support for VET learners. For this, we presented Mixplorer, a system designed to support novices' creative practices by scaffolding the process of design space exploration. Mixplorer uses a genetic algorithm approach we call "social design space exploration" where the designs created by a group of people serve as the starting set of parents in the genetic operations and a novel interface makes it possible to replace the fitness function with a human-in-the-loop. In Study 1, we conducted interviews with garden design instructors and validated the feasibility of using of Mixplorer in a VET setting and the potential benefits for novices' divergent thinking. In Study 2, we conducted a controlled experiment to more-closely investigate whether design mixing provided any special support for novices' creative practices. We found that design mixing provided significantly better support for novices' creativity when compared to no exploration or random exploration, and that those who used the design-mixing interface produced more novel design outcomes than participants in the other groups. Our work shows the importance of scaffolding creative exploration for novice designers and demonstrates the feasibility of using social design mixing for this purpose.

7 General Discussion

7.1 Contributions

The contributions of this thesis can be summarized in terms of the two primary research objectives mentioned in the introduction: (1) exploring possibilities to expand the experience of learners in design-related VET, and (2) investigating the potential benefits of these expanded experiences.

The concept of expanding experience is novel in the VET context and it was the goal of this thesis to explore this new territory. The main contribution of this thesis is that it proposed a new way of supporting VET learners using digital technologies. We focused on design-related professions and investigated how the learners could expand their experiences through exploring digital variations of a design grounded in a real-world experience. Our goal was to support the apprentices in exploring a broader space of designs as a way of compensating for the limited breadth of their real-world experiences. To accomplish this goal, we explored multiple ways of designing digital experiences in order to enrich their real-world experiences. Specifically, we explored three dimensions of expansion: parametric, temporal, and social.

The dimensions of expansion we explored in this thesis are three of many possible directions to expand the VET experience, but we have chosen them based on the problems and the needs of the apprentices. For each dimension, we developed a digital tool that enabled the expansion of experience in that dimension, and we conducted experimental studies to acquire insights into the potential benefits of the expanded experiences. These three examples demonstrated how the concept of expanding experience can be applied to specific professions in concrete scenarios.

In order to investigate the potential benefits of the expanded experience using the tools we implemented, we conducted experimental studies to understand the behavior of the VET learners and the effects on their learning outcomes. As this thesis was exploratory research in a new territory, each of the studies focused on different aspects of how the tool can be used in the VET context. Specifically, the first study investigated the apprentices' ability to navigate a design space and how we can support this process with a structured interface; the second study explored the benefits of a VR tool that allows time exploration of a design and compared it with the traditional paper-sketch interface; and the third study investigated the effect of the social design exploration tool on creativity support and the novelty of design outcomes. With the results from the three studies, we gained insights into how the concept of expanding experience can be applied to the VET learners and how to design the support in the digital tools in order to improve the potential benefits for the learners.

7.2 Summary of findings

For the parametric dimension, we investigated how learners explored a multidimensional space of possible designs and how we could support the exploration process with an interface that disentangled navigation along design parameters. For this purpose, we developed a tool called BloomGraph for bouquet design exploration for florist apprentices and conducted an experiment where we compared the graph-based interface with another interface that provided designs linearly without a structure. Our results showed that the graph-based interface fostered the exploration of more diverse designs and apprentices acquired a better understanding of the space. We also used eye-tracking data to investigate the apprentices' behavior and strategies. Our findings from this study showed that a digital tool can support VET learners with navigating a multidimensional conceptual space of designs, that it could help them acquire a better understanding of the design space, and that both the interface design as well as the strategies adopted by the learners when using the interface affected learning outcomes.

For the temporal dimension, we explored how to support learners in envisioning designs that change over time. We developed a VR tool called GardenVR for gardener apprentices that allowed them to create a garden and explore it in an immersive environment. Using GardenVR, the apprentices were able to experience how a garden would change in time by simulating and visualizing it. In an experimental study with gardener apprentices, we investigated how the VR tool could support learners' creative practices in comparison with the conventional paper-sketch interface. The results showed that the VR interface of the tool had distinct advantages when compared to the paper interface in terms of different aspects of the design quality. Moreover, the order between the two interfaces had a significant effect on the design outcome. We also investigated how the apprentices navigated the time dimension while using the VR tool and found that the temporal aspect of their navigation behavior was one of the factors that differentiated the learners who produced higher-quality designs with the ones that did lower-quality. Our findings suggest that the VR interface can serve a complementary role to the conventional paper-based interfaces, while also suggesting how VR should be combined with the conventional practice (i.e., the order between the two). Additionally, our findings provide guidance about when the temporal exploration should be done within the VR application.

For the expansion in the social dimension we developed a tool called Mixplorer for gardener apprentices that allowed them to create an initial design and recombine it with the designs of other learners. This tool enabled a novel way to explore design spaces in a social manner by using the designs of others as the source of exploration. Using the tool, we conducted two studies. First, we conducted an interview study with garden-design instructors in VET schools. The instructors gave highly-positive feedback and did not anticipate that they would experience much trouble in incorporating the tool into their teaching, and they suggested that the tool might provide benefits for the VET students including the ability to improve their divergent thinking skills. In the second study with novice designers, we investigated the effect of the design-mixing functionality of Mixplorer on creativity support and on the design outcome. The results showed that design mixing can provide a better support for creativity when compared to two other conditions with no exploration and exploration without the mixing functionality. Moreover, the participants generated more novel designs after using the design-mixing interface. Our findings suggest that the tool can be integrated in the VET teaching practices while providing benefits to the learners in terms of supporting a broader exploration of the design space and the production of more novel designs.

7.3 Limitations

The concept of expanding experience has real-world experience as the starting point of the process. The process of expanding experience starts with a real-world situation and the digital experiences we designed are built on top of it. However, in our experimental studies, we did not explicitly explore how bringing real-world experiences into the tools might affect the digital experiences of learners. Because our work focused on the digital experiences (and it is where our contributions are), we controlled for the real-world side of the process in order to more-closely study the effect of the digital activities. In other words, apprentices did not bring their own experiences into the tools we designed. Instead, we provided them with a fixed set of real-world experiences that they could use as starting points. However, allowing apprentices to bring their own experiences into the tools is an important part of the flow that needs further investigation.

The target group of our research consisted of learners in design-related VET and we have worked with two professions, florists and gardeners. The concept of expanding experience using digital variations can be applied to other design-related domains, for example, supporting the exploration of the design space of dresses for fashion designers or chairs for furniture designers. As long as a real-world experience can be represented as a digital design, it can be expanded in a digital space. However, this does not mean that the results we reported in this thesis can be directly generalized to other domains. Further investigations with other VET professions would be required for generalizability.

The studies we presented in this thesis explored multiple aspects of how digital tools might make an impact on learners in VET. As this was a new domain to explore, we decided to focus on breadth, rather than depth, in order to gain a broader understanding. As a consequence, the findings from our studies actually led to producing other interesting questions in different directions. This is a situation that should be addressed with future studies that go more into depth.

7.4 Reflections

The goal of the digital experiences we designed for VET learners was not to simply replicate real-world situations. This is the case with many digital tools, particularly with VR—they try to mimic reality with high-fidelity graphics to make the user feel closer to that reality. Of course a certain level of realism can help learners become immersed in the situation, but that was not the focus of our studies. Our focus was to design digital environments that could allow learners to do *more* than what they are able to do in reality: to make abstract dimensions of a conceptual space visible, to travel in time to see the future of a design, or to create multiple designs instantly by merging yours with your colleague's. We believe that this is the real benefit of using digital technologies in the context of experiential learning. We wanted to create a new reality beyond the everyday reality of the VET learners, to support them in experiencing things that they cannot in the real world.

One of the common findings that links together all the studies presented in this thesis is the importance of guidance in expanding experience. There are an unlimited number of ways to expand an experience with digital variations. If you imagine a design exploration as a combinatorial problem of design parameters (as we did in our first study), there is a combinatorial explosion of the space to be searched only after considering a few parameters. When designing tools to support exploration of these vast spaces, providing guidance for the learners is key and the results from our studies support this argument. The interface that disentangles the dimensions of design parameters can foster a better understanding of the design space (study 1), a paper sketch before the digital experience can act as a guide to creating a better design in VR (study 2), and the design-mixing process can scaffold exploration and lead to producing more novel designs (study 3). These findings provide evidence that expanding experience with digital tools can be more effective for more learners when there is sufficient guidance provided.

We have mainly focused on learning outcomes and design quality as the dependent variables in our studies, however, what is also important in VET is motivation [105]. Although we did not explicitly measure motivation in our studies, it was clear from the reactions of the apprentices and the teachers that they were excited and enthusiastic about the tools we designed for them. What we developed as part of this thesis often surprised these stakeholders and gave them new ideas about what they could do with digital technologies in the context of their learning. The excitement we saw in the eyes of the teenagers was an additional benefit of the digital experience for them.

Another point to be mentioned is related to the recent effort by the Swiss federal government to support the digital transformation of vocational training [117]. The State Secretariat for Education, Research and Innovation (SERI) of Switzerland has been increasingly promoting the adoption of digital technologies in the Swiss VET systems. They support and fund projects that can (1) improve digital skills in school, (2) promote the use of information and communication technologies in teaching and learning, (3) foster rapid adoption of the education system to the requirements of the market, and (4) enhance coordination and communication in education cooperation. Their effort is part of the implementation measures for the 'Vocational Training 2030' project by the federal government [116]. Our work in this thesis is well in line with this effort as we are proposing a new way of using digital technologies to support the VET learners. What is also meaningful is that we focused on the professions for practical design work, who are usually less exposed to digital technologies in their daily work (when compared to bankers and office clerks). The professions doing design work might be small in numbers, but it is important to work with them for reasons of impact and inclusiveness.

It must be emphasized that the digital experiences we designed are not meant to replace the apprentices' real-world experiences. This is why we frame our work as *expanding* real-world experiences with digital ones. As we learned more about the Swiss VET system and how young students become professionals, it only became clearer to us that some things cannot be learned digitally. We cannot show how different flowers smell to florist apprentices, how the earth feels in your hands to gardeners, or how a fresh croissant tastes in your mouth to bakers in a digital world (at least with the currently available technologies). And often these kinds of experiences are what build passion and dedication towards a career. Our work shows that the role of digital experiences is to complement real-world experiences, not to replace them. Our studies showed that digital environments can empower learners to do different things than they can do in the real world, and that the learners benefit more when these digital experiences are combined with a real-world practice so they can complement each other.

7.5 Future work

The results of this thesis suggest multiple directions for future research. One direction is about integrating the digital experiences into the learning journey of VET apprentices. The result of the second study showed the importance of instructional design when combining a digital activity with existing practices. And in the third study, we demonstrated how a digital activity can be designed to fit in a VET classroom setting. What needs to follow as future work is to consider the fit and the integration of these digital activities in a bigger picture. This type of work requires long-term studies that investigate the integration of digital tools into the learning journeys of VET apprentices. Does the digital experience that expands a real-world experience actually help them become better professionals in the long-term? This is an interesting and important question to be answered from pedagogical and policy-making perspectives.

Another direction is related to the use of more advanced technologies for the design generation task, particularly deep learning algorithms. Recent advancement of deep generative models have enabled a new way of generating designs and the quality of these outputs is often beyond our expectations. Leveraging the power of these algorithms would allow for more creative ways to support the learners with design space exploration. In our recent work, we explored this direction with apprentice fashion designers [51]. Our early findings show the potential of generative adversarial networks (GANs) as a way to generate novel designs for learners so that they can explore a more creative space of designs.

Another future direction is concerned with further developing the concept of expanding experience. We can consider two paths forward in this direction. First, future studies can investigate other dimensions of expansion for VET experiences. For example, the cost of different designs might be another dimension worth exploring. Cost is an important criteria in practical situations and we can imagine a digital tool that supports exploring how a design might change based on the cost of producing it. Second, future work should consider expanding this idea to other professions. We focused on design-related professions where the workplace experiences of apprentices can be captured and represented as a digital artefact. However, these professions only make up a small portion of the VET system. Most of the VET professions with higher numbers of apprentices, such as health care workers or commercial employees, do not deal with practical designs in their work. How can we expand the experience of a VET apprentice when the experience cannot be easily captured in a digital form? For instance, for the commercial employees, the profession with the highest number of apprentices in the Swiss VET system, their experience is not related to a design product, but rather to a situation or a scenario. How can we represent their experience as a digital artefact and expand it in a digital space? It is an important direction for the follow-up work of this dissertation in terms of scalability and impact.

In conclusion, this thesis focused on the design of digital tools that can enrich and expand real-world experiences. Digital experiences are becoming more and more important in our daily lives and the border between the real and digital worlds is becoming increasingly blurred. Real-world experiences are becoming digital and digital tools are reshaping the real world. This phenomenon is also affecting the professional world and consequently the VET system, and it is more important than ever to consider how digital experiences should be designed for the learners. In this context, our work demonstrates and emphasizes that it is not simply a matter of replacing a physical experience with a digital one. Rather, digital experiences which connect to, augment, and expand real-world experiences are key to helping achieve VET's digital future.

A Appendix to Chapter 4

A.1 Pre-/Post-test questions

The two types of questions for the pre/post-tests are shown below. The purpose of the test is to see if the participants can understand the bouquet design as a combinatorial problem of different attributes that can take different values. The pre/post-tests were composed of five questions of each type.

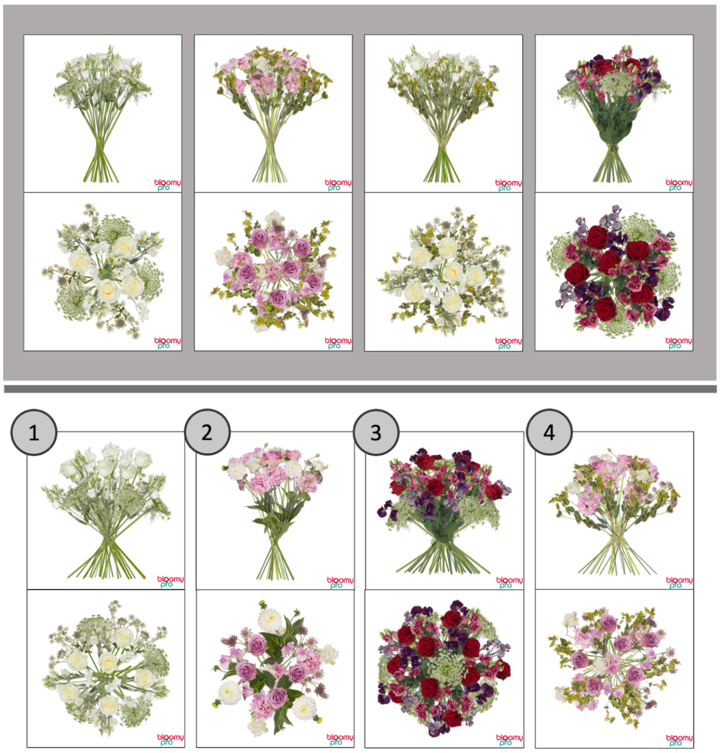

Figure A.1 – A Type 1 question. Participants were asked to select a bouquet that shares an attribute with the four given bouquets in the gray box. Each bouquet is presented with side and top views.

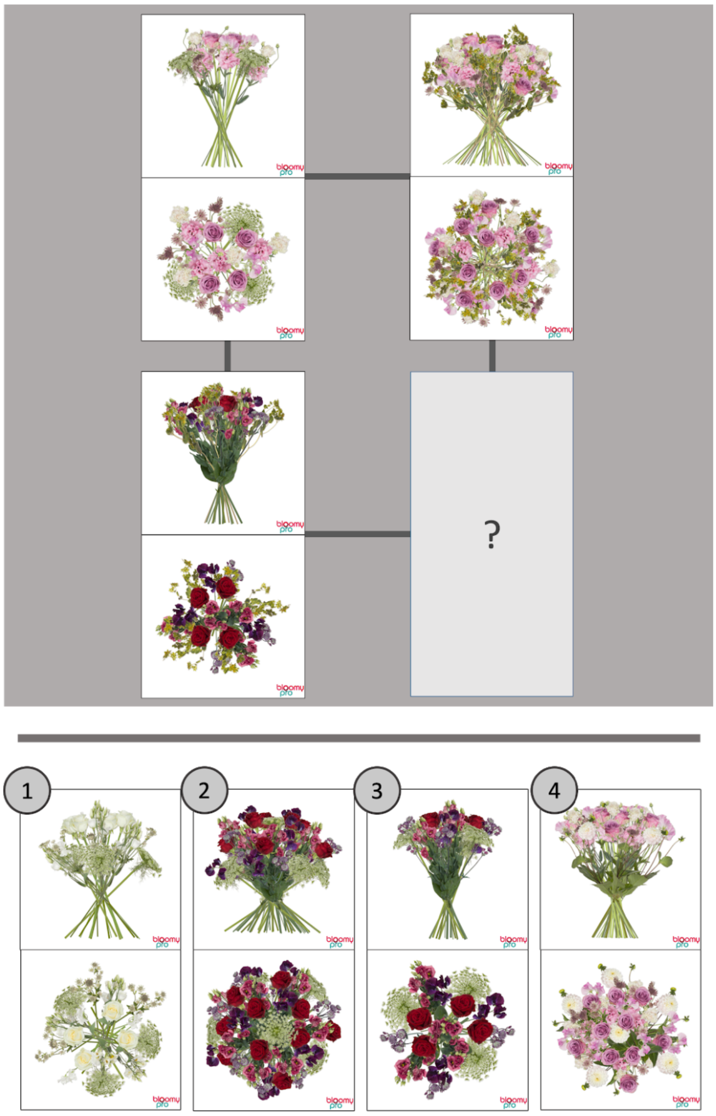

Figure A.2 – A Type 2 question. Participants were asked to find the most appropriate bouquet for the missing box in the relation map.

A.2 Bouquet designs datasets

Figure A.3 – Bouquet designs dataset for Scenario 1 (birthday).

Figure A.4 – Bouquet designs dataset for Scenario 2 (wedding).

A.3 Questionnaire

Fragebogen
Bitte beantworten Sie die folgenden Fragen.

1. Wie alt sind Sie? *(How old are you?)*

2. Was ist Ihr Geschlecht? *(What is your gender?)*
   - Weiblich *(Female)*
   - Männlich *(Male)*
   - Ich ziehe es vor, nicht zu antworten. *(I prefer not to answer.)*

3. In welchem Lehrjahr sind Sie? *(What year of apprenticeship are you?)*

4. Im Allgemeinen, was macht ein gutes Strauß design und was ein schlechtes Strauß Design aus? *(In general, what makes a good bouquet design and what makes a bad bouquet design?)*

5. Welchen Faktor hast du am Anfang am Geburtstagsstrauß geändert? *(Which factor did you change at the beginning of the birthday bouquet?)*
   - Farbe *(Color)*
   - Textur *(Texture)*
   - Form *(Form)*
   - Abstand *(Spacing)*

6. Welchen Faktor hast du am Anfang am Hochzeitsstrauß geändert? *(Which factor did you change at the beginning of the wedding bouquet?)*
   - Farbe *(Color)*
   - Textur *(Texture)*
   - Form *(Form)*
   - Abstand *(Spacing)*

7. Welche Kundeninformationen waren für dich wichtig? Wie hast du sie in Elemente des Blumenstraußes umgesetzt? *(What customer information was important for you? How did you translate them into elements of the bouquet?)*

8. Ich war zufrieden mit dem Blumenstrauß, den ich gewählt habe. *(I was satisfied with the bouquet I chose.)*
Nicht wirklich *(Not really)* 1 — 2 — 3 — 4 — 5 — 6 — 7 Völlig *(Completely)*

9. Was würdest Du ändern, um den Strauss zu verbessern? *(What would you change to improve the bouquet?)*

Was hältst du von deiner Erfahrung mit der Software? War es: *(What do you think about your experience with the software? It was:)*

10. einfach *(easy)* 1 — 2 — 3 — 4 — 5 — 6 — 7 schwierig *(difficult)*

11. zu langsam *(too slow)* 1 — 2 — 3 — 4 — 5 — 6 — 7 zu schnell *(too fast)*

12. verloren *(lost)* 1 — 2 — 3 — 4 — 5 — 6 — 7 klar *(clear)*

13. langweilig *(boring)* 1 — 2 — 3 — 4 — 5 — 6 — 7 Spaß *(fun)*

14. verwirrend *(confusing)* 1 — 2 — 3 — 4 — 5 — 6 — 7 hilfreich *(helpful)*

15. Wie viele Sträuße gab es Ihrer Meinung nach in jedem Szenario? *(How many bouquets do you think there were in each scenario?)*

16. Von der Karte, welcher Weg ist derjenige, der deiner Erfahrung am nächsten kommt? *(From the map, which path is the closest to your experience?)*

- Blau *(Blue)*
- Rot *(Red)*
- Grün *(Green)*

17. Wie oft verwenden Sie Instagram, Pinterest oder ähnliches, um Ideen zu sammeln? *(How often do you use Instagram, Pinterest, or the like to gather ideas?)*
- Täglich *(Daily)*
- Einmal in ein paar Tagen *(Once in a few days)*
- Wöchentlich *(Weekly)*
- Monatlich *(Monthly)*
- Niemals *(Never)*

B Appendix to Chapter 6

B.1 Interview protocol for Study 1

	Topics	Questions
1	Experience with the application	Did you enjoy using the application? Was it easy enough to use?
2		What did you think about the designs you made in the design-mixing process, especially in terms of giving you new ideas?
3		What changes would you make to the design-mixing process that might help you be more creative or generate more interesting designs?
4	Anticipated students' experience	Now we want to ask some questions about your apprentices. Do your apprentices ever have opportunities to work on design problems in the classroom? If so, what sorts of design problems do they typically work on, and what sorts of tools or methods do they use?
5		Let's consider the design-mixing process. Compared to another scenario where apprentices can just see other designs, do you think that the design-mixing could provide benefits, or could it create confusion for the students?
6		In a classroom scenario, students are mixing with designs of their classmates. What are your thoughts on having students mix designs with their classmates (instead of mixing designs made by other people they don't know)?
7		How might you use this application with your apprentices? And would you like to use this application with your apprentices?

8	Divergent thinking	Now we want to ask some questions about one specific topic called 'divergent thinking.' Divergent thinking is defined as the ability to imagine a wide variety of possible solutions for a design problem. Do you think this is a useful skill when working on an open-ended problem such as designing a garden?
9		What is your opinion on your students' ability to engage in divergent thinking?
10		How do you think this application can help students' divergent thinking?
11	Additional questions	Is there anything else about the experience of using the application that you feel strongly about and would like to share with us? (prompts: potential impact on students' motivation, engagement, design outcome)

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EDUCATION

Ph.D., Computer and Communication Sciences Feb 2017 – present
Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland
Computer-Human Interaction for Learning and Instruction (CHILI) laboratory
Thesis: Design and evaluation of digital tools to expand experience in vocation education
Supervisor: Prof. Pierre Dillenbourg

M.S., Robotics Feb 2009 – Feb 2011
Korea Advanced Institute of Science and Technology (KAIST), South Korea
Urban Robotics laboratory
Thesis: Vision-based autonomous 3D navigation of underwater robots
Supervisor: Prof. Hyun Myung

B.A.Sc., Mechanical Engineering Sep 2003 – Jun 2008
University of Toronto, Canada
Graduated with honors

EMPLOYMENT HISTORY

Doctoral Assistant Jan 2017 – present
EPFL, Computer-Human Interaction for Learning and Instruction (CHILI) laboratory
- Conducted research on human-computer interaction and educational technology

Intern Mar 2016 – Dec 2016
EPFL, Learning Algorithms and Systems laboratory
- Conducted research on human motion analysis and robotic systems

Research Scientist Feb 2011 – Feb 2016
Korea Railroad Research Institute, ICT Convergence Research team
- Conducted research on applying ICT to railroad systems

Research Assistant Feb 2009 – Feb 2011
KAIST, Urban Robotics laboratory
- Conducted research on autonomous navigation in 3D space

SKILLS & EXPERTISE

Topics: Human-computer interaction, Behavior analysis, Extended reality, 3D navigation
CS skills: Python, C#, Unity 3D, R
Languages: English (C1), French (A2), Korean (native)

RESEARCH PROJECTS

Mixplorer: Design space exploration for creative design Sep 2020 – present
- Developed a novel mechanism for exploring design space using design mixing
- Conducted a controlled experiment with novice designers to validate feasibility

Garden VR: Garden design and exploration in virtual reality Jan 2019 – Aug 2020
- Designed and implemented a VR tool for designing and exploring gardens
- Conducted an experiment with gardener apprentices to investigate behavior in VR

Learner behavior analysis using eye tracking Jan 2018 – Dec 2018
- Developed a design space exploration tool with graph-based interface
- Conducted an experiment to analyze exploration strategy based on eye movement

CogIMon: Cognitive Interaction in Motion Mar 2016 – Dec 2016
- Conducted human motion analysis for 3D object interaction
- Designed and implemented a robot control system inspired by human motion

Human motion detection system for railroad level crossings Mar 2011 – Dec 2015
- Designed a human detection system using laser range finder for safety monitoring
- Field-tested a prototype for two years and supported commercialization

Underwater robot navigation Jan 2010 – Feb 2011
- Developed an algorithm for autonomous 3D navigation using visual target tracking
- Implemented an autonomous underwater robot platform using the algorithm

Seamless indoor and outdoor localization for robots and humans Feb 2009 – Feb 2011
- Developed a beacon-based localization system for indoor and outdoor
- Achieved a seamless transition with indoor beacons and outdoor GPS

PUBLICATIONS (selected)

Kim, K. G., Davis, R. L., Coppi, A., Cattaneo, A. & Dillenbourg, P. (2022). Mixplorer: Scaffolding design space exploration through genetic recombination of multiple peoples' designs to support novices' creativity. *SIGCHI Conference on Human Factors in Computing Systems* (submitted).

Kim, K. G., Oertel, C., & Dillenbourg, P. (2021). How florist apprentices explore bouquet designs: Supporting design space exploration for vocational students. *International Journal for Research in Vocational Education and Training*, *8*(1), 65–86.

Dobricki, M., **Kim, K. G.**, Coppi, A. E., Dillenbourg, P., & Cattaneo, A. (2021). Perceived educational usefulness of a virtual-reality work situation depends on the spatial human-environment relation. *Research in Learning Technology*, 29.

Kim, K. G., Oertel, C., Dobricki, M., Olsen, J. K., Coppi, A. E., Cattaneo, A., & Dillenbourg, P. (2020). Using immersive virtual reality to support designing skills in vocational education. *British Journal of Educational Technology*, *51*(6), 2199–2213.

Khodr, H., Ramage, U., **Kim, K. G.**, Guneysu Ozgur, A., Bruno, B., & Dillenbourg, P. (2020, October). Being Part of the Swarm: Experiencing Human-Swarm Interaction with VR and Tangible Robots. In *Symposium on Spatial User Interaction* (pp. 1–2).

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Dillenbourg, P., **Kim, K. G.**, Nasir, J., Yeo, S. T., & Olsen, J. K. (2019). Applying IDC theory to education in the Alps region: a response to Chan et al.'s contribution. *Research and Practice in Technology Enhanced Learning*, *14*(1), 1–10.

Lee, D., **Kim, K. G.**, Kim, D., Myung, H., & Choi, H. T. (2012). Vision-based object detection and tracking for autonomous navigation of underwater robots. *Ocean Engineering*, *48*, 59–68.

HONORS AND AWARDS

Management Innovation Award, Korea Railroad Research Institute, March 2014.
Honor Rolls, University of Toronto, 2006 Fall, 2007 Winter, 2007 Fall, 2008 Winter.

REFERENCES

Available upon request