Augmented Reality to Facilitate a Conceptual Understanding of Statics in Vocational Education

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Abstract

At the core of the contribution of this dissertation there is an augmented reality (AR) environment, StaticAR, that supports the process of learning the fundamentals of statics in vocational classrooms, particularly in carpentry ones. Vocational apprentices are expected to develop an intuition of these topics rather than a formal comprehension. We have explored the potentials of the AR technology for this pedagogical challenge. Furthermore, we have investigated the role of physical objects in mixed-reality systems when they are implemented as tangible user interfaces (TUIs) or when they serve as a background for the augmentation in handheld AR.

This thesis includes four studies. In the first study, we used eye-tracking methods to look for evidence of the benefits associated to TUIs in the learning context. We designed a 3D modelling task and compared users' performance when they completed it using a TUI or a GUI. The gaze measures that we analysed further confirmed the positive impact that TUIs can have on the learners' experience and enforced the empirical basis for their adoption in learning applications.

The second study evaluated whether the physical interaction with models of carpentry structures could lead to a better understanding of statics principles. Apprentices engaged in a learning activity in which they could manipulate physical models that were mechanically augmented, allowing for exploring how structures react to external loads. The analysis of apprentices' performance and their gaze behaviors highlighted the absence of clear advantages in exploring statics through manipulation. This study also showed that the manipulation might prevent students from noticing aspects relevant for solving statics problems.

From the second study we obtained guidelines to design StaticAR which implements the magic-lens metaphor: a tablet augments a small-scale structure with information about its structural behavior. The structure is only a background for the augmentation and its manipulation does not trigger any function, so in the third study we asked to what extent it was important to have it. We rephrased this question as whether users would look directly at the structure instead of seeing it only through a tablet. Our findings suggested that a shift of attention from the screen to the physical object (a structure in our case) might occur in order to sustain users' spatial orientation when they change positions. In addition, the properties of the gaze shift (e.g. duration) could depend on the features of the task (e.g. difficulty) and of the setup (e.g. stability of the augmentation).

The focus of our last study was the digital representation of the forces that act in a loaded structure. From the second study we observed that the physical manipulation failed to help apprentices understanding the way the forces interact with each other. To overcome this issue, our solution was to combine an intuitive representation (springs) with a slightly more formal one (arrows) which would show both the nature of the forces and the interaction between them. In this study apprentices used the two representations to collaboratively solve statics problems. Even though apprentices had difficulties in interpreting the two representations, there were cases in which they gained a correct intuition of statics principles from them.

In this thesis, besides describing the designed system and the studies, implications for future directions are discussed.

Key words: Augmented Reality, Learning Technologies, Qualitative Statics, Vocational Training, Tangible User Interfaces, Physical Interaction, Magic-lens Augmented Reality

Abstract

Il fulcro di questa tesi è un ambiente di realtà aumentata (RA), StaticAR, che supporta l'apprendimento della statica nel contesto della formazione professionale dei carpentieri. Gli studenti di carpenteria dovrebbero sviluppare un intuizione di questi argomenti piuttosto che una comprensione formale. Abbiamo quindi esplorato il potenziale della RA per questa contesto pedagogico. Inoltre, abbiamo studiato il ruolo degli oggetti fisici nei sistemi a realtà mista, sia come interfacce utente tangibile (TUI) sia quando servono da sfondo per la RA su dispositivi tablet.

Questa tesi comprende quattro studi. Nel primo studio abbiamo usato metodi di oculometria per cercare prove dei benefici associati alle TUI nel contesto dell'apprendimento. Abbiamo progettato un'attività di modellizzazione 3D e confrontato le prestazioni degli utenti quando l'hanno completata utilizzando una TUI o una GUI. Le misure ottenute hanno ulteriormente confermato l'impatto positivo che le TUI possono avere sull'esperienza degli studenti.

Nel secondo studio abbiamo valutato se l'interazione fisica con modelli di strutture possa portare a una migliore comprensione dei principi di statica. Ventiquattro studenti hanno partecipato ad un'attività in cui potevano manipolare dei modelli fisici dotati di componenti meccanici che consentivano di esplorare come le strutture reagiscono ai carichi. L'analisi delle prestazioni e dei movimenti oculari degli apprendisti ha evidenziato l'assenza di chiari vantaggi nell'esplorazione della statica attraverso la manipolazione, che invece impedirebbe agli studenti di notare aspetti rilevanti per risolvere problemi di statica.

Dal secondo studio abbiamo ottenuto le linee guida per progettare StaticAR come un sistema *magic-lens*: un tablet "arricchisce" una struttura su scala ridotta con le informazioni sul suo comportamento strutturale. La struttura è solo uno sfondo per l'RA e la sua manipolazione non innesca alcuna funzione. Quindi, nel terzo studio ci siamo chiesti se fosse importante avere la struttura. Più precisamente, abbiamo esplorato in quali circostanze gli utenti guardano direttamente la struttura invece di vederla attraverso il tablet. I risultati suggeriscono che uno spostamento dello sguardo dallo schermo all'oggetto fisico (una struttura nel nostro caso) si verifica quando gli utenti cambiano posizione al fine di sostenere il loro orientamento spaziale. Inoltre, le proprietà di tale spostamento dello sguardo (p.es. la durata) dipendono dalle caratteristiche del compito che si sta svolgendo (p.es. la difficoltà) e della RA (p.es. la stabilità).

Infine ci siamo concentrati sulla rappresentazione digitale delle forze presenti in una struttura. Nel secondo studio abbiamo osservato che la manipolazione fisica non ha aiutato gli studenti a comprendere come le forze interagiscono tra loro. La nostra soluzione è stata quella di combinare una rappresentazione intuitiva (molle) con una leggermente più formale (frecce), in modo da mostrare sia la natura delle forze sia l'interazione tra loro. Nel quarto studio, ventidue studenti hanno utilizzato le due rappresentazioni e collaborato per risolvere dei problemi di statica. Anche se hanno avuto difficoltà nell'interpretazione delle due rappresentazioni, ci sono stati casi in cui gli studenti hanno mostrato una corretta intuizione dei principi di statica.

In questa tesi, oltre a descrivere il sistema progettato e gli studi, sono discusse anche implicazioni per direzioni di ricerca future.

Parole chiave: Realtà Aumentata, Tecnologie per l'Apprendimento, Approccio Qualitativo alla Statica, Formazione Professionale, Interfaccia Utente Tangibile, Interazione Fisica, Realtà Aumentata Magic-lens

Contents

List of Figures

List of Tables

1 Introduction

1.1 Motivation

The brochure of the Holzbau-Schweiz, a large association of Swiss carpentry industrialists, declares that “no other country provides a better training in wooden carpentry than Switzerland does” (Holzbau-Schweiz, b). The training is mostly based on the alternation between school and workplace: apprentices spend part of the week at the vocational school and the rest at the companies with which they have a contract. In 2013 a new ordinance related to carpentry apprenticeship was issued (Holzbau-Schweiz, c). The ordinance extended the apprenticeship duration from 3 years to 4 years in order to meet the requirements of the job market. Among the eleven new training topics that have become part of the curriculum, one is statics and physics of structures.

Carpenters who have completed the four-year apprenticeships are not supposed to check the stability and safety of the structures they work on. However, they are responsible for the correct execution of jobs, following the instructions received from carpentry foremen, architects or engineers. In a report about the principal causes of failures in timber constructions from the division of structural engineering of the Lund University (Frühwald and Thelandersson, 2008), the authors found that 19.7% of the failures are due to errors during the erection of the structures on the construction site. Even though Switzerland was not included in this report, it implicitly shows the reasons why a correct intuitive understanding of statics is a necessary competence to be acquired during the apprenticeship.

The relevance of statics has been increased rather than introduced from scratch. The old curriculum mostly encompassed the analysis of simple systems (e.g. a cantilever beam) and the principles of mechanical properties of materials. For these introductory topics, teachers could rely on a variety of physical materials and practical examples to complement their lessons, and, consequently, apprentices could appreciate the concreteness of what is written in their textbooks. The practical approach, however, does not suit well complex scenarios, thus the need for new tools that could assist teachers and students to meet the new learning objectives.

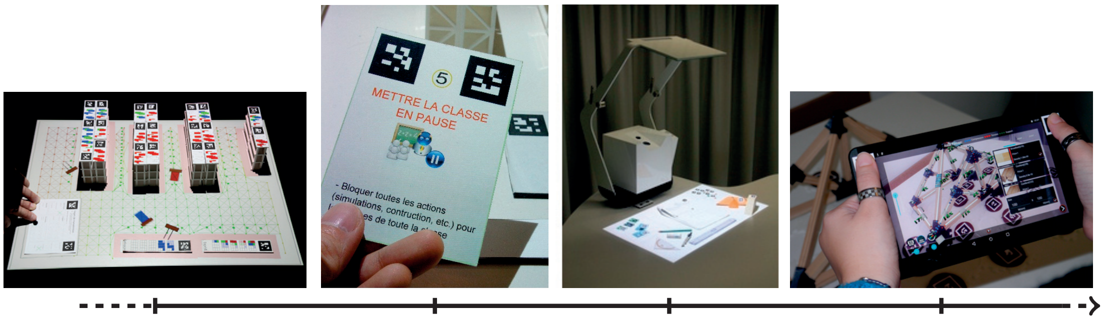


Figure 1.1 – Research on augmented reality applications for Swiss vocational education and training.

How can apprentices acquire an intuitive understanding of statics? Could they gain it by analysing the structures they encounter on the construction sites, discussing the challenges posed by renovating a house frame, confronting the different types of residential roof truss?

Solutions for promoting a conceptual and qualitative understanding of the phenomena related to the physics of structures could be found in previous works (Brohn and Cowan, 1977; McCrary and Jones, 2008). However, these works have been framed generally within the boundaries of high school or academic education. To our knowledge, studies that took into account the specificities of the vocational learning context are scarce, as well as learning instructions and technologies designed for this context (Rauner and Maclean, 2008). Motivated by these observations, we have hypothesized that the development of an augmented reality environment could be a viable solution to introduce the new topics in vocational classes. Augmented reality has found wide application in the learning domain (Wu et al., 2013). For what concerns its application within the Swiss vocational context, our expectations found justifications in the insights given by the works of Zufferey, Do-Lenh and Cuendet (Zufferey, 2010; Do-Lenh, 2012; Cuendet, 2013). Zufferey developed TinkerLamp, a tabletop environment featuring tangible and paper interfaces that was designed to be part of the training activities for logistics apprentices. The multiple external representations available in Zufferey's TinkerLamp (digital augmentation, small-scale physical models and paper-based interfaces) supported the acquisition of abstraction skills by apprentices who could better synthesize the concepts taught at school with the experience gained in the warehouse. Successively, Do-Lenh studied the aspects of TinkerLamp related to the collaboration and orchestration of vocational classrooms. He highlighted the design aspects that allows for the integration of AR technology within the pre-existing resources and practices available in the classes and that help teachers to take advantage of episodes that are potentially interesting for learning. Lastly, Cuendet developed TapaCarp, a tabletop system whose interface and activities aimed at facilitating the acquisition of spatial skills during carpentry training. Hence, he extended the previous findings to a new

profession and also provided a contribution to the research about the benefits of tangible interaction in AR learning technologies.
The work described in this thesis concerns the adoption of augmented reality for the purpose of a new pedagogical challenge.

This work has given us the opportunity to investigate aspects of AR technologies that are not strictly related to the learning context. In particular, we investigated how the presence of physical objects impacts users' experience in mixed-reality systems. Physical objects can provide input (e.g. Tangible User Interfaces) and, in such a case, the design of their appearance goes hand in hand with the design of their functions in the digital space. This implies the need for guidelines to explore the design space, as well as the need for empirical studies upon which refining these guidelines (Marshall, 2007; Antle and Wise, 2013). Even when the physical surroundings are not explicitly meant to be functional in the AR experience, their presence has an impact on the users' perception of the space, whether it is the physical space or the augmented space. Understanding how users move between and within these spaces is crucial to better characterize the technologies that populate the mixed reality continuum. It can also contribute to the implementation of mechanisms that sustain users' perception in immersive digital environments.

1.2 Research Objectives

Our research objectives were the following.

- **Exploring how augmented reality could support apprentices in learning concepts related to statics in a qualitative way.** This process began by investigating the strengths and limitations of an approach purely based on the manipulation and exploration of physical materials, since this approach is close to the pre-existing "practitioner" culture. From the results, we derived the elements that compose our AR system, StaticAR. These elements, in particular the graphical representation of statics entities (forces, stress, supports, etc.), have been evaluated in their ability to promote a conceptual understanding of statics.
- **Investigating the influence of physical objects on the users' experience when interacting with AR systems.** In particular, we hypothesised that the perceptual benefits associated to usage of physical objects as input (TUIs) would emerge from the users' gaze behavior. In addition, we studied the occurrence of a shift of visual attention from the screen to the physical environments when using a handheld AR device, hypothesizing that the influencing factors could be found in users' spatial abilities, in AR faults or in the navigation of the physical and digital spaces.

1.3 Thesis Roadmap

The next chapter clarifies the concept of qualitative understanding and provides an overview of the pedagogical practices and technologies employed to promote it in the fields of statics and analysis of structural behavior. This chapter presents also the features of the augmented reality technology, along with the bases for its adoption as a learning technology. The last part of the chapter introduces the research methodology and the terminology related to the eye-tracking methods which have been used in three of the studies we conducted.

Chapter 3 completes the introduction by presenting the Swiss vocational eduction system and the dual approach school-workplace. It also describes our research framed within Dual-T project, a research program founded by the Swiss State Secretariat for Education, Research and Innovation. In a nutshell, the program aims at bridging the dual contexts of vocational education, school and workplace, through technologies that allow apprentices to share their experiences between these two contexts. Finally, the carpentry training and the role of statics in it, including the suggestions and recommendations of the teachers collected during these four years, conclude this chapter.

The studies that have been conducted are described in chapters 4, 5, 7 and 8. The first study and the third one (chapters 4 and 7) investigated aspects related to the usage of physical entities in AR systems based respectively on tangible interaction and on handheld devices. The study in chapter 5 explored the effectiveness of hands-on strategies for our learning objectives. Based on the results of the study we designed StaticAR, which is presented in chapter 6. In chapter 8, StaticAR has been used to run a collaborative activity involving pairs of apprentices. This last study explored how apprentices statics' reasoning was affected by the graphical representations displayed by StaticAR and it identified common difficulties among the learners.

The main findings of our work, its limitations and the future research directions that derived from it are finally summarized in chapter 9.

2 Related Work and Research Methodology

The work presented in this thesis has been built upon multiple areas of research which can be categorized in the two macro blocks of Learning Science and Human-Computer Interaction. The first section of this chapter reviews the works that are relevant to qualitative physics, statics and structural behavior, which belong mostly to educational research in STEM fields (engineering, architecture, etc.). The second section is dedicated to Augmented Reality, including a parenthesis on tangible interaction and Tangible User Interfaces. This section provides an introduction to such technologies and outlines the bases for the adoption of augmented reality in the educational domain. The last section concludes this chapter by recalling our research objectives and explains their contribution to previous works. Moreover, it presents the research methodology and the eye-tracking terminology that we used in three of our studies.

2.1 Qualitative or Conceptual Understanding of Physics Concepts

Throughout this thesis, the use of terms like *qualitative*, *intuitive* or *conceptual* understanding of physics concepts is recurrent and almost interchangeable. Hence an analysis of their meaning is essential for a better understanding of the topic.
The word *qualitative* usually opposes to *quantitative* and denotes an understanding through reasoning processes that relies on discrete representations of the physics behaviors rather than on continuous quantities (Bredeweg and Struss, 2003). Reformulating the example of Forbus about how a moka pot works (Forbus, 1990), the answer given by most people denotes a qualitative understanding of such process. People usually know that the bottom chamber should be filled with water that gets heated up and generates steam. They probably know that the steam pushes the water and so the coffee comes out. As a consequence, people are aware of the danger of explosions in case the two parts are not tight, although a safety valve is present. This knowledge is not associated to the myriad of equations describing the thermodynamics process, yet it is powerful enough to correctly describe the process and to achieve the goal of making coffee.

In this thesis, the adjective *intuitive* has often a positive value, however unusual this might seem to the reader. In cognitive science literature, this term could be found as synonymous of *naïve or folk* knowledge which have been used mainly with a negative connotation to indicate the body of common-sense beliefs that learners exhibit (Keil, 2003). The negative connotation comes from the fact that these beliefs (or intuitions) are identified with the pre-existing erroneous conceptual knowledge which represent the main obstacle to the development of a correct understanding (Vosniadou, 2002). Conversely, I use the expression *gaining an intuitive understanding* to denote the acquisition of a correct and informal common-sense knowledge, as the one reported by Roschelle and Greeno when describing how experienced physicists approach a physics problem (Roschelle and Greeno, 1987), and to refer to development of the ability to rapidly evoke particular aspects relevant to the problem and its solution observed by Lakin (Larkin et al., 1980).

Conceptual understanding appears often together with *qualitative reasoning* within the educational literature. Although the word *conceptual* is widely employed, it refers to a vague idea of deep knowledge which has not been clearly defined yet (Sands, 2014). Scott, Asoko, and Leach (Scott et al., 2007) defined *concepts* as "basic units of knowledge that can be accumulated, gradually refined, and combined to form ever richer cognitive structures". Similarly, Rittle-Johnson (Rittle-Johnson, 2006) explained "conceptual knowledge as the understanding principles governing a domain and the interrelations between units of knowledge in a domain", which is opposed to procedural knowledge, namely the ability to perform actions in order to solve a problem in a familiar context.
Without going any further on the general discussion about the meaning of *conceptual*, in regards to statics and structural behaviour the term will refer to the mastering of structural knowledge as seen by Pier Luigi Nervi:

> The mastering of structural knowledge is not synonymous with the knowledge of those mathematical developments which today constitute the so-called theory of structures. It is the result of a physical understanding of the complex behavior of a building, coupled with an intuitive interpretation of theoretical calculations. ((Pedron, 2006, citation of Pier Luigi Nervi,1956))

It is noteworthy that this interpretation does not neglect the quantitative aspect, but it rather suggests conceptual understanding as a necessary complement and precondition to the successful interpretation of the numerical results.

What are the difficulties in gaining qualitative understandings of statics? Typical mistakes are related to the identification of the external forces acting on a single body, to the description of how the forces from multiple bodies interact with each other, or to the specification of the conditions for the static equilibrium (Steif and Dantzler, 2005; Call et al., 2015; Yilmaz, 2010). The difficulties in correctly achieving these tasks can be traced back to the misconceptions associated to Newtonian mechanics. Hestenes and colleagues delineated a taxonomy of common misconceptions exhibited by students in (Hestenes et al., 1992). From their taxonomy the

authors derived the “Force Concept Inventory”, a tool to assess the conceptual understanding of forces and motion. The origin of many of these beliefs is related to what is observed during the everyday experience. For instance, a widely known misconception is that the motion of a body implies the presence of an active force. The justification is that bodies are naturally at rest in the daily experience and that they move only when pushed or pulled. Another example related to the 3rd law of Newton is the common belief that the force exerted by a large body on a small one is stronger than the reaction force exerted by the small body.
The fact that these misconceptions are so rooted in the everyday phenomena makes them difficult to replace and it poses a challenge to learners who have to solve a conflict between a new piece of information and the pre-existing knowledge. Ploetzner and VanLehn (Ploetzner and VanLehn, 1997) attributed the failure in gaining qualitative knowledge to three possible causes: (1) important information could not have been presented to learners; (2) learners could not have had enough time to familiarize with a new concept; (3) students might not have engaged enough in the learning activity in order to accommodate the new piece of information within their pre-knowledge in order to solve possible misconceptions. The first two issues can be addressed by improving the instructional materials, for example adopting alternative representations for the same concept (de Dios Jiménez-Valladares and Perales-Palacios, 2001; Hinrichs, 2005; Savinainen et al., 2013). The latter requires the adoption of teaching strategies promoting a conceptual change. The success of any educational strategies (e.g. collaborative activities, problem-based works, etc.) depends on the extent to which the learners’ misconceptions and misunderstanding emerge during the learning activity and how their change is promoted (Guzzetti et al., 1993; Schroeder et al., 2007).

2.1.1 Technology-Enhanced Approaches for Learning Statics

According to Brohn and Cowan (Brohn and Cowan, 1977), qualitative understanding is “unlikely to be learnt as a by-product of quantitative analysis. It is worthy of consideration and treatment in its own right, and requires special attention”. Among the available textbooks that approach the subject from such angle, it is worth to mention Brohn’s *Understanding Structural Analysis* (Brohn, 2008). The book has been structured as a series of worked exercises about different topics (trusses, frames, arches, etc.) in which the author created a graphical language and diagrammatic exploration in order to guide the learner in analysing structural behavior (Figure 2.1). Interestingly, in the recent years, the book became also part of a commercial educational tool for teaching structural analysis by Armfield Ltd (Armfield, Figure 2.2). The tool features a software that uses the same visual language adopted in the book to represent the effects of loads on the structures. In addition, sensors and actuators could be interfaced with the software in order to setup hands-on experiments.

This kind of integration of *active learning* sessions along with the traditional textbook-based ones is perceived to be particularly useful by students who crave for “seeing” what they learn on the books. As a consequence, some universities have reformed their curricula to accommodate this need. At the EPFL, the course “Structures I” is provided in form of MOOC

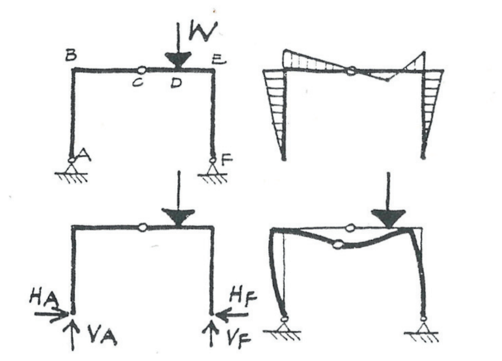


Figure 2.1 – Brohn's diagrammatic representation of the effect of a vertical force on a frame.

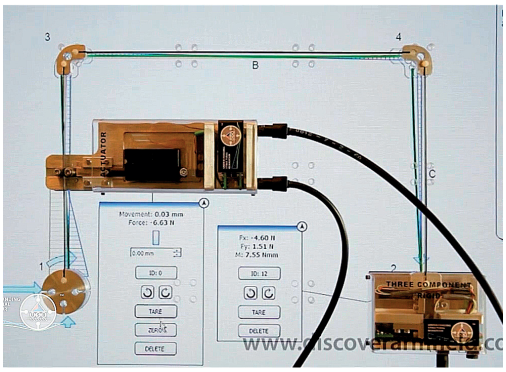


Figure 2.2 – Armfield Ltd. tool for exploring structural behavior.

(Massive Online Open Course) on the platform Coursera[1]. The lessons of the online course are complemented with virtual lab activities running on the platform *i-structures* (Burdet and Zanella, 2004). The platform includes a collection of interactive applets in which students can access different analysis tools (e.g. Cremona diagrams, frame analysis) and use them to solve the exercises proposed by the professors. The graphical language used in the applets makes *i-structures* suitable also for high-school students who have not acquired yet the mathematical tools needed for approaching statics in a formal way. Another notable example is from the ETH Zurich, where the teaching of structural behavior has been enriched by the usage of the e-learning platform *EasyStatics* (Anderheggen and Pedron, 2005, Figure 2.3). Similarly to *i-structures*, *EasyStatics* provides a virtual structural laboratory in which students can freely explore structural analysis. The results of the analyses have been represented both numerically and graphically, which makes the platform "intuitive as a hand calculator and as engaging as a video game". Moreover, the online capabilities include the support for team work, communication among the students and tools for the teachers (e.g. sending materials, downloading students' submissions).

Another online platform that aims at improving the qualitative understanding of structures is the *Expedition Workshed* whose main feature is the extreme gamification of the learning experience (Senatore and Piker, 2015). The platform features Java applets like *Catastrophe* and *PushMePullMe* which hide an accurate physics engine behind a playful interface. In *Catastrophe*, the learner is asked to remove as many elements as possible without making a structure collapse. The level of stress in each member of the structure is displayed in real-time, hence the player can recognise the contribution of each member to the overall stability. In *PushMePullMe*, the user can use the mouse to pick an element of the structure and drag it around (Figure 2.4). The dragging is converted in an external load and its effect is displayed in real-time.

According to May and Johnson's report about the teaching of structural behavior at univer-

[1] `http://edu.epfl.ch/coursebook/fr/structures-i-CIVIL-122`

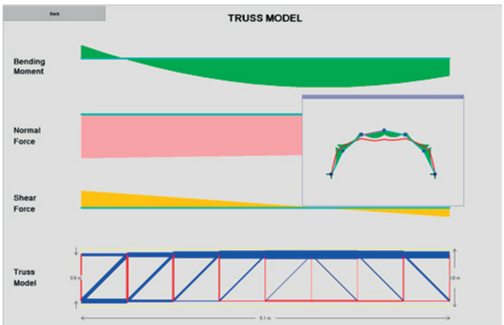


Figure 2.3 – EasyStatics: truss analysis example.

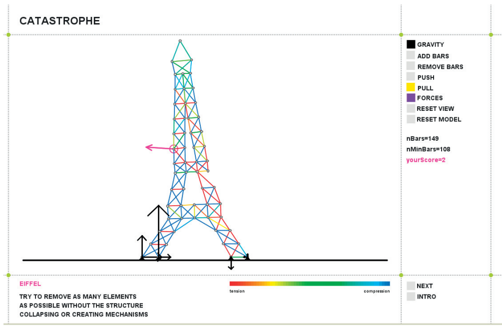


Figure 2.4 – Catastrophe from Expedition Workshed.

sity level (May and Johnson, 2008), students tend to have a strong preference towards the approaches that integrate practical activity, for example hands-on design or manipulation of physical models.

Romero and colleagues reported two successful case studies of such teaching approaches that were implemented at the University Jaume I de Castellon, Spain (Romero and Museros, 2002a). Students were engaged in project-based sessions where they iteratively (1) designed a structure, (2) built it with balsa wood or commercial kits and (3) checked its strength via software. The blend of practical work and traditional numerical analysis made students interpret the quantitative results in lights of the qualitative predictions and observations made during the design process. In this way, the connection between theory and practice was strengthened and the effects of misusing the computer-based analysis emerged too.

A more recent work describing a successful case study of project- and problem-based strategies could be found in (Solís et al., 2012). At the Universidad de Sevilla, these learning methodologies have been applied from the third to fifth year of mechanical engineering curriculum. Throughout the three years, students were involved in practical activities ranging from designing, building and testing small-scale wooden structures, such as roofs or bridges, to collecting data from real structures in order to provide practical ground to advanced topics. The comparison between this innovative approach and the traditional one showed an increment in both students' pass rate and grade point average, as well as a higher satisfaction of both students and teachers.

In the galaxy of educational technologies tailored for structural analysis and statics there are also a few works featuring mixed-reality systems. Two examples of pioneering virtual reality systems for studying structures are in (Chou et al., 1997; Setareh et al., 2005). In these studies students were projected into virtual spaces by wearing head-mounted displays. The virtual environments offered capabilities similar to those available in Computer-Aided Design software (designing structures, changing materials, running simulations), along with an immersive user experience. In terms of learning effectiveness, in (Setareh et al., 2005) the authors found an absence of a significant effect of the virtual immersion on students' outcomes. The virtual reality was as effective as a simple desktop-based visualization, although

more engaging and more natural to interact with.
Augmented reality applications are gaining momentum too. In (Rodrigues et al., 2008), the authors described an AR system to display the behavior of a beam. By means of fiducial markers, the system was able to detect the point where the user applied the force and to display the forces inside the beam and its deflections (Figure 2.5). In another work on beam behaviour, Takouachet and colleagues developed a prototype of tangible interface that could infer the forces applied by the user and display the resulting deformation (Takouachet et al., 2012). The interface allowed the user to explore how different materials affect the deformation and the breaking point of the beam. A recent system that featured advanced analysis capabilities was described in (Huang et al., 2015). The AR application integrated wireless sensor measurements with a real-time finite element analysis core in order to display the effects of external loads directly on real-world objects. In one of the case studies, the tool was used to show the stress in a stepladder after a person stepped on it (Figure 2.7).

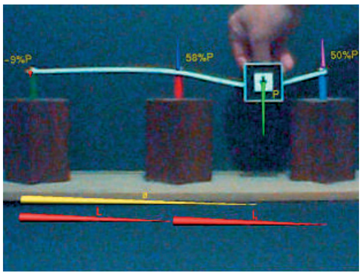


Figure 2.5 – Augmentation of a supported beam from (Rodrigues et al., 2008).

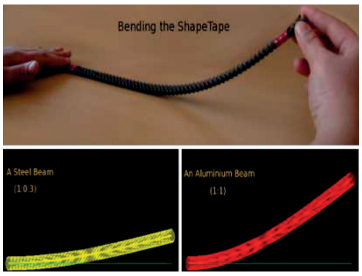


Figure 2.6 – Tangible user interfaces for physically-based deformation (Takouachet et al., 2012).

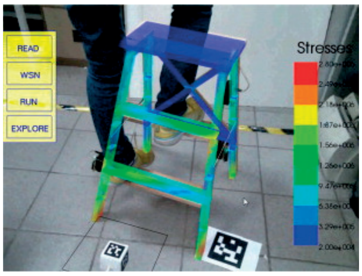


Figure 2.7 – Finite element analysis displayed on real-world objects (Huang et al., 2015).

2.2 Augmented Reality

In recent years there have been several attempts in defining augmented reality (AR) in a clear way. However, since AR is such an umbrella term, Azuma's broad definition remains one of the most commonly accepted (Azuma, 1997): Augmented Reality is technology that has three key requirements, namely (1) it combines real and virtual content, (2) it is interactive in real time, (3) it is registered in 3D. Augmented reality enhances users' perception of the physical reality by overlaying it with digital contents. It belongs to the class of Mixed-Reality technology, along with virtual reality (VR) systems. However, differently from VR, AR techniques are not immersive and do not throw users in a virtual space. Users keep their view of the world, which gets complemented with computer generated content rather than being replaced. Following the cinematographic metaphor proposed by (Azuma, 1997), AR experience is similar to the one portrayed in the movie "Who Framed Roger Rabbit?", in which real people interacted with animated cartoon characters within the physical world (Figure 2.8). Instead, virtual reality is closer to the setting of Disney's Tron where people are digitalized and assimilated in a computer generated environment (Figure 2.9). Cinematography aside, probably the best-known characterization of AR is from (Milgram et al., 1994), where this technology figures half way in the Reality-Virtuality continuum, between completely real environments and completely synthetic ones (Figure 2.10).

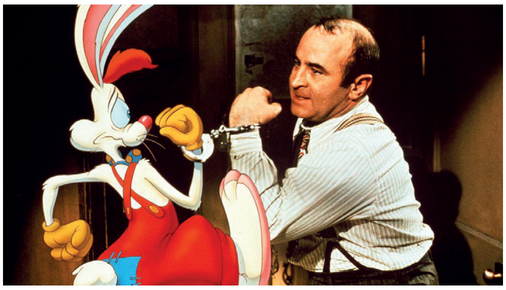


Figure 2.8 – A scene from “Who Framed Roger Rabbit?”.

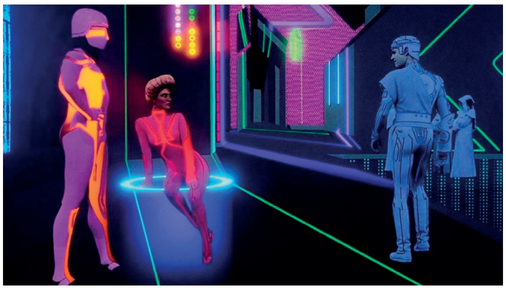


Figure 2.9 – A scene from “Tron”.

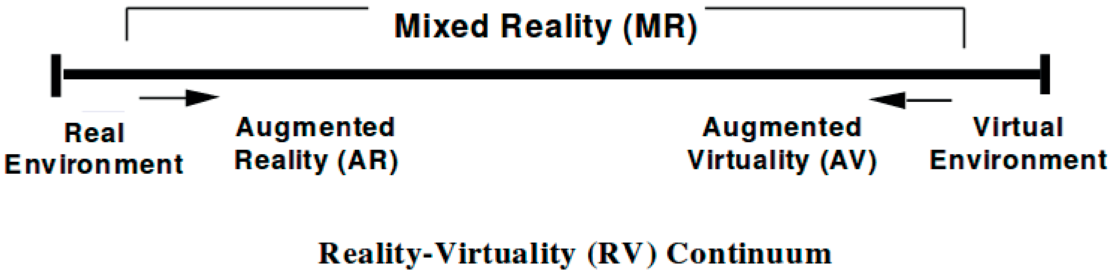


Figure 2.10 – Reality-Virtuality Continuum from (Milgram et al., 1994).

Multiple taxonomies have appeared in order to characterize the countless systems available in the literature. These have been roughly divided in four categories by Normand et al. (Normand et al., 2012):

Technique-centered These taxonomies put emphasis on the features of the techniques used to implement the augmentation. An example is from Milligram and colleagues (Milgram et al., 1994), who defined three axes according to following criteria: (1) the amount of information that the system knows about the environment; (2) the quality of the digital representation (e.g. photo realistic, wireframe, etc.); (3) the extent to which the user feels present, which is related also to the class of displays (e.g. head-mounted, handheld, etc.).

User-centered Hugues et al. proposed a functional characterization based on two criteria: the goal of the augmentation and the way the artificial content is created (Hugues et al., 2011).

Information-centered The criteria for these taxonomies focus on the way the information is presented. For example the usage of either 2D or 3D graphics and the arrangement of the digital information around the physical source (e.g. superimposed or detached).

Tönnis, Plecher and Klinker considered also a temporal dimension which differentiates augmentations that are updated continuously in time (e.g. car speedometer) or discretely in time (e.g. GPS indications) (Tönnis et al., 2013).

Interaction-centred These last taxonomies encompass the works focusing on the interaction paradigms. For instance, Mackay built her classification on the target of the augmentation (Mackay, 1998): the user (e.g. wearable devices), the objects (e.g. tangible or paper-based interaction) or the physical surrounding (e.g. projection in public spaces, collaborative augmented workspaces).

In the same article (Normand et al., 2012), Normand and colleagues have also proposed a synthesis of these classification criteria in their taxonomy which includes four axes: (a) temporal base, which distinguishes augmentation related to situations in the past (e.g. archaeological sites), present, future (e.g. augmentation of construction sites) or imaginary situations; (b) tracking degrees of freedom; (c) augmentation type, which can be mediated or direct; (d) the rendering modalities axis, which considers interaction paradigms complementary to the visual one, such as haptic, voice, olfactory, collaborative, etc. The last three axes are now discussed in more details.

Tracking Methods Tracking techniques are basically of two natures. They can be *sensor based*, which rely on position sensors like geomagnetic field sensor, inertial measurement unit or GPS, and *vision based*, which make use of computer vision techniques on camera streams. Depending on the hardware availability, some tracking approaches are hybrid and fuse data from sensors and cameras to improve the performance.

Sensor-based approaches provide location-based information when the important aspect is to know the position and orientation of the user rather than what the user is observing. Besides being largely used in commercial applications, sensor-based systems are widely found in the educational domain to implement *enhanced context teaching* strategies. These strategies encourage students to make connections between what is taught and their environment which can be, for instance, the school or the city. An example is the EcoMOBILE experience (Kamarainen et al., 2013) which implemented a form of outdoor activity for learning ecosystem science concepts during which students localized hotspots using the GPS and collected data that were lately used in the classroom discussion.

Vision based techniques involve computer vision methods for recognising, tracking and estimating the pose of objects in the scene. The usual pipeline for monocular model-based 3D tracking of rigid objects consists in (1) detecting (or tracking) features in the image; (2) matching these features with the ones extracted from the target objects beforehand, whose 3D positions are known; (3) compute the 3D positions of the objects (Lepetit et al., 2005). Vision based techniques could be subdivided in three classes based on the variations in the previous steps (Zhou et al., 2008):

(a) AR based on fiducial marker detection in an application for teaching geometry (Bonnard et al., 2012a).

(b) Markerless AR for animating museums paintings (Lu et al., 2014).

(c) Model-Based AR using a 3D mesh for improving the tracking (Vacchetti et al., 2004a).

Figure 2.11 – Vision-based tracking methods.

Marker-based The detection is narrowed down to the identification of particular landmarks (fiducial markers) in the image whose appearance is very distinctive. Fiducial markers offer a robust tracking and 3D pose estimation, although they need to be placed in the environment in advance and might be aesthetically unpleasant.

Natural Features-based These algorithms are similar to the previous one, except that they are based on the detection of unique features in the objects being tracked, such as points of high contrast and lines visible on textured objects. An initialization phase is usually required to create the set of visual features describing the target objects and their correspondences with 3D points. During the tracking, the goal of the algorithms is to find those features in the input images. By matching the features from the camera image with the features previously known, it is possible to retrieve the pose of the object. The main advantage of these approaches is that the environment is not altered by the introduction of artificial elements. However, in order to extract features, the target objects should present rich textures. Moreover, the detection could be affected by the quality of the input image and by environmental changes like lighting conditions.

Model-based These algorithms make use of models of the object to be detected, such as 3D mesh or the 2D silhouette of the object to be detected. Combined with the extraction of natural features, these algorithms usually improved the robustness of the pose estimation and the tolerance to mismatches (Vacchetti et al., 2004b). Furthermore, they could also deal with the detection of texture-less objects through the detection of lines and edges (Wang et al., 2017). The main drawback is the necessity of having a prior 3D model of the target object. Some recent works overcame this limitation by employing visual-SLAM algorithms for reconstructing the scene (Li et al., 2017) or depth sensors (Park et al., 2011).

Displays and Information Location In Normand and colleagues' taxonomy, mediated and direct argumentation describe respectively applications in which the content is provided

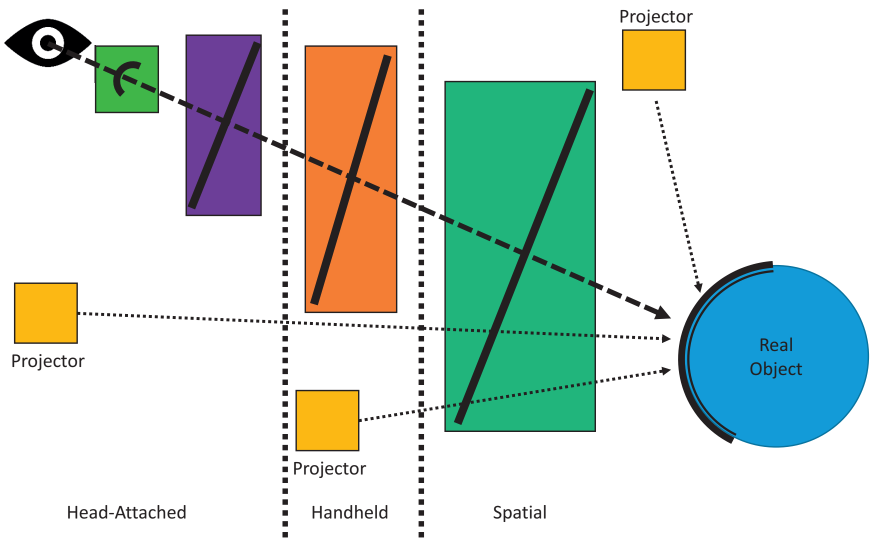


Figure 2.12 – An illustration of the different locations of the displays, of the places where the digital information could be shown (solid line) and of the two types of overlay (planar or curved). Adapted from (Bimber and Raskar, 2006).

through a device (e.g. head-mounted displays) and applications that rely on the projection of the augmentation (e.g. tabletops). A complete description of the variety of display solutions presented in AR works was provided by Bimber and Raskar in (Bimber and Raskar, 2006, Chapter 2,Figure 2.12).

Depending on their spatial arrangement, the authors distinguished head-attached displays, hand-held displays and spatial displays.

Head-attached displays require users to wear a gogles-like device which either shows or projects on the surrounding the digital information. The fact that these devices are usually cumbersome, heavy and offer a limited field of view has limited there spreading outside the research labs. Recently commercial solutions have been released, offering more comfortable solutions and software development tools which would allow for a massive diffusion of mixed-reality applications.

The second class of displays (hand-held) is probably the most common solution thanks to the widespread availability of smartphone and tablet devices. The class includes solutions featuring hand-held projectors too. Video see-through is the preferred paradigm implemented with such systems, which could result in various interaction metaphors. Two examples are the *peep-holes* and the *magic-lens* in which users employ the device to disclose information concealed in the physical surroundings (Bier et al., 1993). Compared to the other two classes, an advantage of hand-held devices is the possibility to “exit” the augmentation just by moving the screens away. However, the main drawbacks are the limited screen size, the reduced field of view and the fact that the rendering is performed using the camera perspective rather than the user’s one (Čopič Pucihar et al., 2014).

The last class includes video see-through and optical see-through systems employing LCD screens, transparent screens, optical holograms, as well as projections onto surfaces via

projectors. Spatial displays make the AR experience shareable among multiple people, thus they are suitable for collaborative working and learning environments or for art exhibitions (Clay et al., 2014). The augmentation becomes accessible from different points of views, which facilitate the development of common ground and enables simultaneous control (Caballero et al., 2014).
Regarding the perceptual issues experienced by the users depending on the display types, Kruijff and colleagues made a synthesis of the perceptual trade-offs across common displays that is reported in (Kruijff et al., 2010).

Tangible Interaction The last axis of the taxonomy is related to the interaction paradigms that complement the visual experience. As it is not the scope of this paragraph to cover the innumerable solutions reported in the literature, I will leave this topic behind and I will rather take the opportunity to introduce a popular solution: tangible interaction.
Tangible interaction encompasses the techniques in which the digital information is embedded in physical artefacts and/or is manipulated through them (Shaer and Hornecker, 2010). Historically, the metaphor of physically manipulating the intangible data could be traced back to the work of Fitzmaurice and the one of Hiroshi and Ullmer (Fitzmaurice and Buxton, 1997; Ishii and Ullmer, 1997). The former coined the term *Graspable Interface* whereas the latter extended it by introducing the term of tangible user interfaces (TUIs). Hiroshi and Ullmer's idea of *Tangible Bits* consisted in three key concepts: (1) coupling the bits with the atoms in order to make data graspable; (2) turn any physical surface into an interactive interface; (3) augment the peripheral space in order to make users aware of background information too. Tangible tools bind their digital and physical representations by sharing properties like geometry, shape, color or position relative to other entities.
TUIs do not always feature strongly within accounts of augmented reality, even though they are both located in proximity on the left side of the Reality-Virtuality continuum and they often overlap. The original definition was very broad and in recent years the borders of what could be considered a tangible UI became even more blurred. For instance, Hornecker and Buur (Hornecker and Buur, 2006) made a distinction between tangible interaction and TUIs, suggesting that the former is a broader term which also includes bodily interaction.
An extensive review of tangible interfaces, taxonomies and related research areas is offered in (Shaer and Hornecker, 2010). The purpose of this brief introduction was to present the concept of TUIs which has been the focus of our first study. Furthermore, the benefits associated to tangible interaction are discussed in the following section.

2.2.1 Augmented Reality in the Learning Domain

In technology-enhanced learning literature, AR learning environments have been presented along with a variety of instructional and learning approaches (e.g. inquiry-based learning, problem-based learning, game-based learning) (Wu et al., 2013). The following sections present a summary of the perspectives providing both the foundations to the adoption of the augmented reality in the educational practices and several design guidelines.

Spatial Cognition

There is a general agreement in considering the learning benefits of augmented reality applications and TUIs in reference to the support that these technologies offer to the users' spatial cognition.
The term *spatial cognition* comes in a nuances of meanings. It can mean the ability to navigate a space or to reason about spatial relationships or to mentally rotate 3D objects. These many facets are shown in Figure 2.13, which depicts a map of them as sketched by Slijepcevic in (Slijepcevic, 2013, chapter 2).

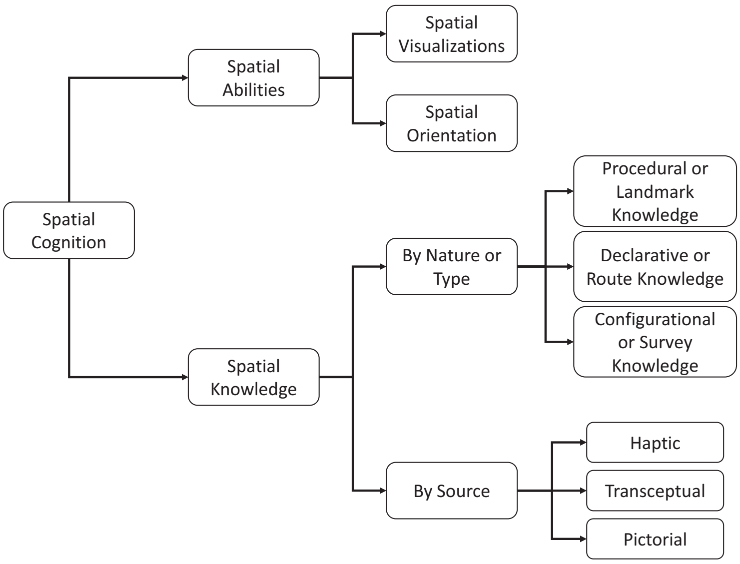
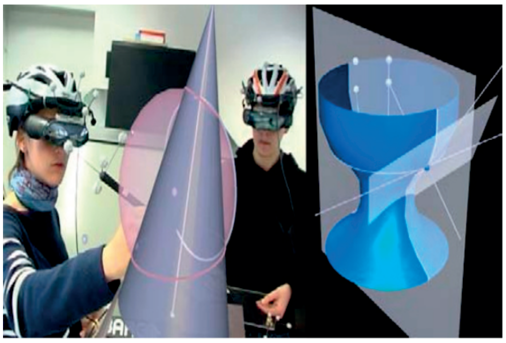


Figure 2.13 – Components of spatial cognition. Adapted from (Slijepcevic, 2013).

The first branching differentiates between spatial abilities and spatial knowledge. Within spatial abilities, a distinction has been made between "the ability to mentally manipulate, rotate, twist, or invert a pictorially presented stimuli" (visualization) and "the comprehension of the arrangement of elements within a visual stimulus pattern and the aptitude to remain unconfused by the changing orientation in which a spatial configuration may be presented" (orientation, Strong and Smith (2001, quotes from McGee (1979))).
On the other branch, spatial knowledge is about acquiring awareness of the spatial configuration of 3D spaces from a geographical perspective. Mark proposed two classifications, by type and by source (Mark, 1993). The types could be knowledge about objects and landmarks (declarative), knowledge as wayfinding (procedural) which is usually acquired by navigating the space, and lastly map-like knowledge (configurational) which implies understanding of spatial relationships. In addition, the source of the spatial knowledge could be from touching or bodily interaction (haptic), visual experience (pictorial) or inference during wayfinding

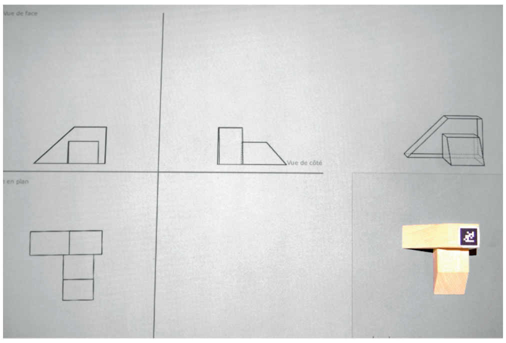
(transperceptual).

Given the relevance of spatial visualization skills to multiple educational fields (e.g. STEM, vocational training, etc.), their malleability has been the focus of several works that have proposed AR systems and TUIs to train spatial skills. In (Dünser et al., 2006), the authors made a comparison between four strategies to train spatial abilities. The first group used an AR 3D construction tool (Figure 2.14a). The second group used a similar tool, but this time the interface was the traditional mouse and keyboard GUI. The third and fourth groups were control conditions in which participants respectively either attended geometry classes or did not receive any additional training. By employing four different psychometric tools to estimate spatial visualization skills, the authors concluded that an increment was visible after the training, regardless of the conditions. Hence, although AR was shown to be effective, it was not superior to other methods.
Based on the previous study, Martín-Gutiérrez and colleagues developed a low-cost webcam based AR application called AR-Dehaes (Figure 2.14b), aiming at training spatial skills by providing students with a series of exercises (Martín-Gutiérrez et al., 2010). The comparison between AR-Dehaes and a control group showed that students who had used the augmented reality tool achieved higher scores than their colleagues in both the mental rotation test and the differential aptitude test, confirming the effectiveness of AR for spatial training purposes.
In the context of vocational training, Cuendet et al. (Cuendet et al., 2012a,b) explored the possibility of training spatial skills with a tabletop system. In (Cuendet et al., 2012a) the authors made a comparison between two design choices: using a tangible control having the same shape as its digital representation, or using one whose shape was unrelated to it (Figure 2.14c). The conclusion was that both design variations led to an improvement of spatial skills, but participants' performance in the task were higher when the digital and physical shapes were identical. In the second study described in (Cuendet et al., 2012b), the difference between the two conditions was in the way the physical actions were coupled with the digital information. Participants had to place a physical object in a way that its orientation and position matched a given 2D silhouette. In one condition, moving the object immediately resulted in updating its digital silhouette, hence it was possible to compare it with the given silhouette (dyna-linking). In the other case, there was no coupling, which increased the difficulty of the task since participants had to use their mental rotation abilities more. A pre-/post-test assessment of the learning gain was done by asking participants to solve some exercises concerning orthographic projections. The conclusion of the study was that, even though the task performance was higher when the manipulation of the tangible object was triggering the update of the digital representation, a significant improvement of between pre- and post-test was only found in the non-coupling condition. The increased usability offered by the real-time feedback translated into poor learning outcomes.
Lastly, it is worthy mentioning the work of Quarles and colleagues, who ran a comparative study about training students at using anaesthesia machines with an AR tangible system, with a GUI system or with an actual anaesthesia machine (Quarles et al., 2008). The study revealed that, whereas there was a negative correlation between perceived task difficulty and spatial



(a) AR 3D construction tool from (Dünser et al., 2006).

(b) An exercise from AR-Dehaes (Martín-Gutiérrez et al., 2010).



(c) Tapacarp, the tabletop system from (Cuendet et al., 2012a).

Figure 2.14 – Three AR systems for developing spatial abilities.

abilities in the case of participants who used the GUI and the actual machine, the correlation was absent for those using the augmented reality. Hence, the authors concluded that AR tangible systems could mitigate the effect of low spatial abilities on users' tasks .

The fact that AR systems blend the virtual world and reality, rather than replacing the latter, preserves people' self-perception of their bodies in the physical environments supporting their spatial orientation. According to Carmichael, Biddle and Mould (Carmichael et al., 2012), a design advantage of AR is its compatibility with the *physical mnemonics*, a form of body-relative interaction described in (Mine et al., 1997) which involves storing and recalling information about virtual objects relative to the body. Shelton and Hedley suggested that, besides keeping intact the procedural and configurational knowledge of the physical surroundings, AR also provides configurational knowledge about both the digital objects and their relations to physical entities (Shelton and Hedley, 2004). Contrary to virtual reality systems, the body movements retain their coherence in both the digital and physical space, avoiding the feeling of disorientation that is common in immersive technologies.

In addition to physical mnemonics, AR supports also two other forms of body-relative interaction, namely *direct manipulation* of the virtual objects and *gestural actions* to issue commands

(Mine et al., 1997). AR applications, especially those involving tangible interactions, are often designed to present a natural mapping between the users' actions and their effects on the digital entities. Having such explicit causal-link facilitates the "translations" of users' intentions (what to do) in actions. An explicative example is from (Price and Falcão, 2009), in which the authors used a tabletop application to teach the property of light (Figure 2.15). In this setup, a physical torch was used as interface for changing the source and the direction of the light beam. Hornecker and Buur referred to this design aspect as *Isomorph Effects* or *Perceived Coupling* (Hornecker and Buur, 2006). It could be also drawn a parallel with the reality-based interaction framework of Jacob and colleagues, who encouraged interaction designer to "leverage users' knowledge and skills of interaction with the real world. [...] The goal is to give up reality only explicitly and only in return for other desired qualities, such as expressive power, efficiency, versatility, ergonomics, accessibility, and practicality" (Jacob et al., 2008).

An interaction based on natural affordances could be detrimental too if it induces unmet expectation. For instance, the torch in the tabletop system was manipulated in the 3D space at the beginning of the interaction, and, similarly, the switch was expected to turn on the beam. Thus, the interface "torch" was partially ambiguous and the users (mostly kids) became aware of the constraints of the tabletop only after some time. A similar case could be found in (Hornecker, 2012), where children used an AR-book to see the characters of the tales in 3D and to interact with them using fiducial markers (Figure 2.16). The children often manipulated the markers in order to achieve actions that were not implemented in the system, although they were plausible and suggested by the tangible nature of the interface. In light of these issues, some authors made a call for *seamful* designs, as opposed to seamless design, in which the *functionality and the internal connections between various parts of a system would be understandable to users in how they were connected and in some sense why* (Sundström et al., 2011).

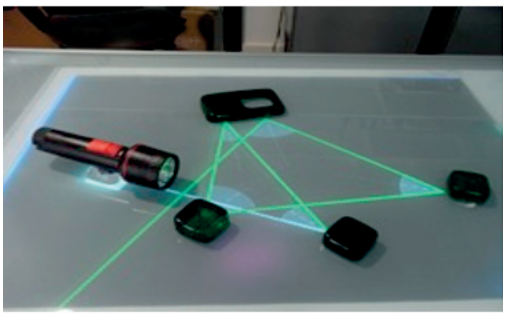


Figure 2.15 – The tabletop system for learning about the behavior of light (Price and Falcão, 2009).

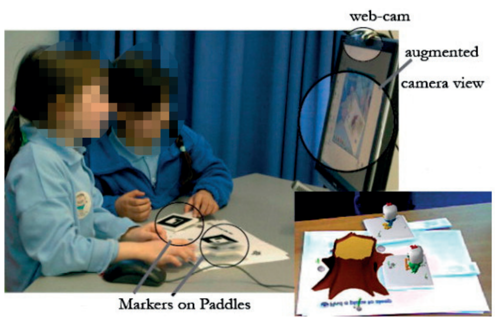


Figure 2.16 – AR-Jam, an augmented storybook (Hornecker, 2012).

Revealing the Invisible, Cognitive Load Theory and External Representations

AR technology is often said to "reveal the invisible", for instance when explicitly representing the interactions between atoms or molecules (Cai et al., 2014), or, in a boarder sense, when offering external representations that scaffold learners' reasoning (Sotiriou and Bogner, 2008). It can be argued that this is not an exclusive feature of augmented reality, but that a simulation on a desktop computer would reveal the invisible too. However, what AR uniquely offers is to do it while remaining in the real world. We are not referring to the potential of AR technology for situated learning, which will be discussed later. We rather refer to the benefits of situated visualizations (White and Feiner, 2009), which is accessing the digital information without de-contextualizing it from the physical reality. We can consider the following scenarios: two carpentry apprentices are analysing the effect on the snow load on the roof of a structure whose small-scale model is given to them. In one scenario the students make a model of the roof on their laptops, run the simulation and conclude that a pillar at the centre of the roof is needed to increase the stability. They add the new bearing element in the simulation and the structure becomes more stable. Hence, they propose this solution to their teacher. In the other scenario the apprentices perform the same steps with an AR tool showing exactly the same information shown on the laptops. They reach the same conclusion, add the new element and the AR simulation reports that the structure gains stability. However, when they observe the augmentation they realize that the pillar leans on the floor, which cannot provide the support considered in the simulation. They conclude that they have to find another solution. The information shown to the students in the two scenarios was exactly the same. In both cases the technologies revealed the invisible (visualizing the forces) and the students added a pillar in their digital model even though it was not possible to do it in the small-scale model (altering the reality overcoming practical limitations). However, in the AR case the fact that the digital information has been embedded within the physical reality made the difference in telling a viable solution from an impractical one. The example could sound contrived, but we believe that it does not describe an unlikely scenario.

Another interesting view about the potentials of AR in the educational field is offered by the works that discuss such potentials by considering the Cognitive Load Theory (Sweller et al., 1998). The theory takes into account the capabilities and limitations of the human cognitive architecture and provides guidelines for designing instructional materials. The general assumption is that problem solving activities require an extensive usage of the working memory, which is known to have a limited capacity. Sweller suggested that the memory load could be due to: (1) the inherent difficulty of the problem or, more generally, of the instructional topic (intrinsic load); (2) the difficulty in comprehending the instructional materials, like visualizing a 3D object from its 2D sketch (extrinsic load); (3) the effort in assimilating the new information, categorizing it and building relationships with the other ideas (germane load). Thus, an optimal design is one that reduces the extraneous load in order to leave free resources for the other two. The support to spatial cognition and the natural affordances discussed so far could be seen as a facilitation provided by the augmented reality that might attenuate extraneous cognitive load.

Positioning the augmentation close to the relevant physical entities provides an external representation that allows users to offload some information from the memory. In (Tang et al., 2003), the authors compared users' mental load in an assembly task when using a head-mounted display (HMD) AR implementation, a HMD implementation without spatial registration[2], a GUI system and paper-based instructions. The results revealed that the medium of instructions had an effect on the mental load. The spatial registration offered by the AR implementation decreased the mental load, because the participants did not have to remember the spatial relationship between the assembly pieces, that, when needed, were already displaced rotated in place.
The external representations are not limited to being memory aids, but, for instance, they could also serve as bridge between representations at different levels of abstraction (Zufferey et al., 2009). A complete discussion about the roles of external representations and their nature is offered by Zhang in (Zhang, 1997), whereas their benefits have been summarized by Ainsworth (Ainsworth, 2006), who also provided the functional taxonomy shown in Figure 2.17 , along with design guidelines.

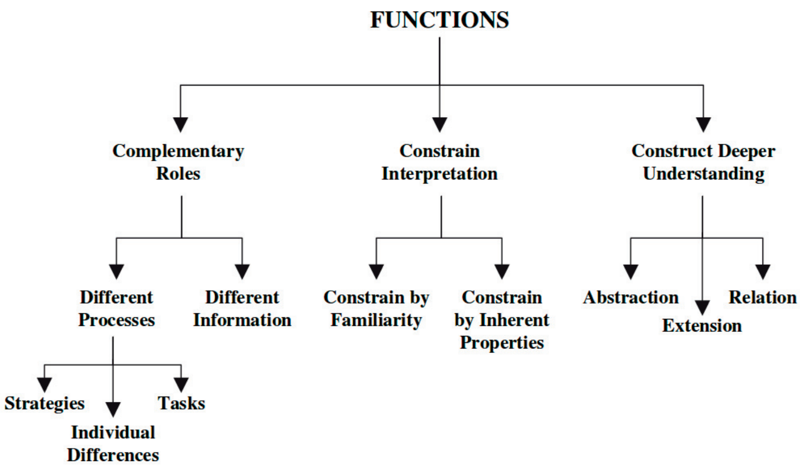


Figure 2.17 – Ainsworth's functional taxonomy of multiple representations (Ainsworth, 2006).

Using this framework, the author explains how increasing the redundancy of representations increases in turn the learners' chances to make connections among representations that differ in format. The difficulty of creating such connections decreases if the representations are co-present. This explanation connects to another result of the experiment about the assembly task (Tang et al., 2003): compared to the paper-based instructions, participants who used the AR system did not suffer the split attention effect. Split attention effect is a difficulty arising from keeping the attention between multiple sources of informations that are either spatially or temporally separate. Kim and Dey referred to the spatio-temporal gap between physical and digital spaces with the term "cognitive distance" which comprises two components (Kim and Dey, 2009). The first component is the effort required to move from the

[2]The instructions were images from a static perspective viewpoint.

physical space to the information space and to look up the relevant resources. The second component is given by the effort of moving back and applying the gathered information. Since the negative effect of the cognitive distance increases with the increasing of frequency of swifts, the general guideline is to minimize the discontinuity between the information space(s) and the real world. Thanks to the digital-physical overlap, AR systems have an advantage over other techniques in avoiding the split attention effect. Nevertheless, avoiding the split attention effect remains a design aspect not to be underestimated; it requires the implementation of specific strategies to deal with (Liu et al., 2012). Two examples of such strategies are the view management technique proposed in (Tatzgern et al., 2014, Figure 2.18), which keeps the relevant information in proximity of the related real-world objects avoiding overlapping and cluttering, and the attention funnelling technique described in (Biocca et al., 2006, Figure 2.19), which aims at driving users' visual attention on the task-relevant areas of the screen.

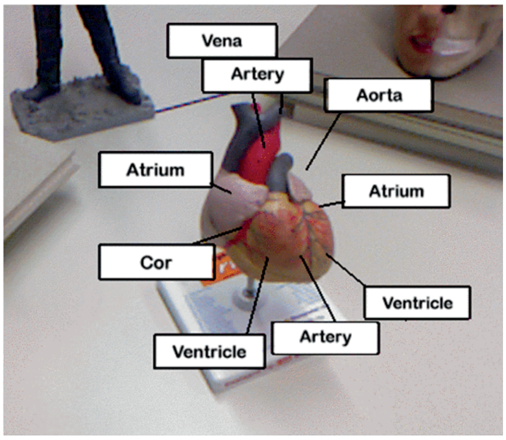


Figure 2.18 – View management technique from (Tatzgern et al., 2014).

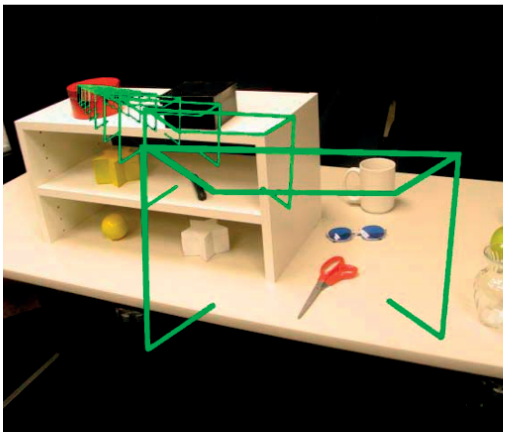


Figure 2.19 – Attention funnel technique from (Biocca et al., 2006).

Physical Manipulation

As previously said, an additional source of spatial knowledge (haptic) becomes available to users when tangible interaction is implemented, which, for instance, might lead to a more readily comprehension of three-dimensional shapes compared to the cases when only the pictorial source is available (Gillet et al., 2005). Besides serving as spatial aids, the learning benefits associated to tangible interaction with artefacts are similar to the ones associated to *physical manipulatives*. In mathematics education, it is a common strategy to promote the understanding of concepts through physical manipulation, e.g. algebra or geometry (Leong and Horn, 2011; Bonnard et al., 2012b). Carbonneau et al. reviewed the theoretical basis for the adoption of manipulatives and outlined four potential moderators derived from human development and cognitive theories (Carbonneau et al., 2013): (a) supporting the development of abstract reasoning; (b) stimulating learners' real-world knowledge; (c) providing the learner with an opportunity to enact the concept for improved encoding; (d) affording opportunities for learners to discover mathematical concepts through learner-driven exploration. A theoretical account of the benefits that the physical manipulation might have on the learning processes could also be found in the embodiment theory, as discussed in (Pouw et al., 2014; Abrahamson and Bakker, 2016). Similar motivations have also served to employ physical manipulation beyond maths education, for instance to implement inquiry-based activities and hands-on learning in other scientific courses like chemistry, physics or biology (Schroeder et al., 2007).

Despite the theoretical ground, some scepticism has arisen towards the general optimism that surrounds the adoption of physical manipulation in instructional materials, thus researchers have tried to disentangle the factors influencing the success of strategies based on them (McNeil and Jarvin, 2007; Carbonneau et al., 2013). Several authors focused on distinguishing the effects due to physicality from those due to manipulation, meant as having control on the instruction (e.g. discovery learning). Among these studies, Klahr and colleagues presented an experiment with 2 (physical vs. virtual manipulatives) x 2 (guided vs. independent instructions) design, in which children explored mechanics by building a mousetrap car (Klahr et al., 2007). The analysis of pre-and post-test showed that children learned equally well in all conditions, thus the authors suggested that the choice of materials could be taken considering other factors like cost of implementing such strategies or re-usability of the materials. Similar conclusions were reached by Marshall et al., who employed the same design for an experiment about adults' understanding of the balance beam behavior (Marshall et al., 2010). Zacharia, Loizou and Papaevripidou reached slightly different conclusions in (Zacharia et al., 2012). The task required children to understand how a beam balance works. However, the "guided vs. independent instructions" was replaced by "correct vs. incorrect instructions". Hence a correct description of the beam balance was introduced to the children in two experimental groups, whereas an incorrect one was proposed in the other two groups . When the description was correct, no difference in the learning outcomes emerged between virtual and physical materials. However, a difference in conceptual understanding appeared between them when the description was incorrect. The physicality helped children in gaining a correct understanding of the problem, whereas students who used the virtual manipulative could not correct their knowledge. Hence, the physical experience appeared as a prerequisite to correctly understand the balance beam behavior. Recently, Brinson has offered a review of over 50 empirical studies comparing non-traditional (virtual and remote) and traditional (physical and hands-on) laboratories in terms of learning outcomes (Brinson, 2015). The comparison did not reveal any supremacy of one class of approaches on the other.

In a nutshell, what emerges from these studies is a clear need for empirical contributions to address whether, why and in which circumstances physical manipulation might have any effect on learning.

Bridging Formal and Informal Learning, Collaborative Learning

When sensor-based tracking was introduced in the previous section, the EcoMOBILE experience (Kamarainen et al., 2013) was cited as an example of how AR could be used to connect different learning places, such as school and the surrounding local parks. The possibility to

carry around the knowledge and to present it in an authentic setting reflects the potentials to make use of AR for *situated learning*. The term refers to a theoretical view which claims that "learning, thinking, and knowing are relations among people engaged in activity in, with, and arising from the socially and culturally structured world" (Lave, 1991).
The theme is particularly relevant to this thesis, given that the context of the research was the Swiss vocational education and training. In Switzerland, vocational apprentices learn in multiple contexts, like schools and companies[3]. The effectiveness of such an educational system depends on the interconnection of the learning experiences made in different contexts. Digital spaces can support the development of this interconnection (Schwendimann et al., 2015). A tabletop AR system designed for such purpose is the Thinker Environment (Zufferey, 2010, Figure 2.20). This learning environment allows apprentices in logistics to learn about warehouses optimization by creating their own layouts and simulating their performance. Compared to the traditional paper-based exercise, the topics taught in school no longer appear abstractions, but they get situated in the daily workplace experience. Furthermore, the learning environment empowers students by giving control over a simulated warehouse, which is something they could never practice in their companies. Thus, they become *practitioners*: they could bring their experience to the workplace and discuss with their senior colleagues about it.

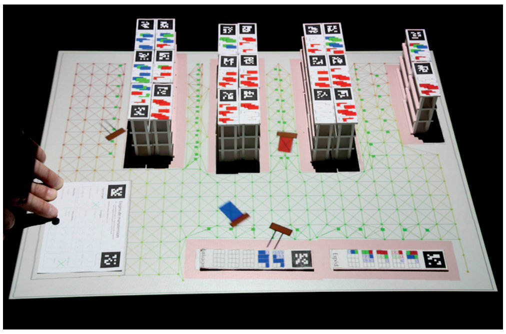


Figure 2.20 – Thinker Environment: a learning environment for apprentices in logistics (Zufferey, 2010).

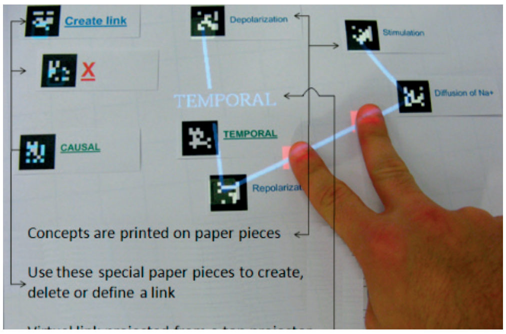


Figure 2.21 – AR tabletop for creating concept-maps (Do-Lenh et al., 2009).

Another feature of the Thinker Environment was the design oriented towards collaborative rather than individual learning activities. Collaboration in learning has been broadly defined as "a situation in which two or more people learn or attempt to learn something together", although the definition remains arguable for some authors (Dillenbourg, 1999). Systems that employ medium-long distance display (e.g. handheld or tabletop) offer shared spaces around which learners can focus, promote joint attention and awareness, and allow for group dynamics in which students (and teachers) can have different roles or permissions for actions (Falcão and Price, 2009; Dillenbourg and Evans, 2011; Schneider et al., 2011). Obviously, having a collaboration-friendly tool does not guarantee the success of a collaborative activity. Instead, it is necessary to have a rationale behind the expected positive outcome, which informs the

[3] The details of the Swiss vocational system will be presented in the next chapter.

mechanisms, constraints and guides of the collaborative interaction (Dillenbourg, 2002). An example of unsuccessful collaboration using tabletops is given by the comparative study in (Do-Lenh et al., 2009). Participants were asked to collaborate in order to produce a concept-map about a neurophysiologic phenomenon. They were split in groups of three people and assigned to two conditions. In the former, the concept-map was built using a software on a desktop-pc whose interface was the traditional mouse-and-keyboard one. In the other condition, the maps were built by arranging paper labels representing concepts, which were recognized and augmented by a tabletop system (Figure 2.21). The results showed that in the tabletop conditions, the learning outcomes were lower than in the other group. In the desktop-pc condition, the access point to the interface was single, since there was only one mouse. Thus, participants were implicitly forced to collaborate, to argue and to find agreements before implementing a change in the concept-map. Conversely, the tabletop offered multi access points, hence each student could *control* an area of the map. This resulted in episodes of working in parallel rather than together and, consequently, in poor collaboration.

Focusing on structuring the collaboration at group level might still not be sufficient if the learning activity takes place in a classroom (Prieto et al., 2014). This perspective has been discussed by Cuendet and colleagues, who put the emphasis on the usability at a classroom level, meant as designing AR-based learning environments by taking into account classroom constraints (Cuendet et al., 2013). The authors proposed five design principles, which, if correctly implemented, contribute to reduce the orchestration load of the classroom, that is "the effort necessary for the teacher – and other actors – to conduct learning activities in the classroom": (**Integration**) Integrating the system in the classroom workflow, avoiding single activities that abruptly modify the course of the class; (**Empowerment**) Allowing the teacher to keep control over the students' interactions, for example providing tool for grabbing their attention; (**Awareness**) Providing teachers with ways to monitor students' needs and progresses; (**Flexibility**) Adapting the activity to unexpected changes in the classroom, such as numerically unbalanced groups; (**Minimalism**) Avoiding overwhelming students and teachers with unnecessary information and only representing only those relevant at a given time.

2.3 Refined Research Objectives

The reader might have got an idea of the numerous opportunities of research that arise from the overview presented so far. An aspect that several scholars have highlighted is the limited investigations of the relations between AR features (situated visualization, physicality, multiple representation, etc..) and learning processes, outcomes and experience (Cheng and Tsai, 2013; Radu, 2014). Consequently, there is a need for expanding the empirical basis that informs the design of mixed-reality learning environments, also in regard to the application to specific subjects (maths, physics, biology, etc.). Along with the development of the AR system, we made our contribution to the research discussion by:

Chapter 4 Providing empirical work on the benefits attributed to physical interaction in a mixed reality system, in line with the suggestions of (Marshall, 2007; Wu et al., 2013; Antle and Wise, 2013).

Chapter 5 Investigating whether and how the manipulation of physical artefacts might aid the comprehension of statics and structural behavior.

Chapter 7 Exploring the nature of shifting the visual attention from the digital augmentation to the physical representation in order to gain an insight about the role of the latter when using handheld AR systems.

Chapter 8 Evaluating the effect of different representations of the physics entities on carpentry apprentices' reasoning about statics problems.

2.3.1 Research Approach

Multiple research strategies have guided the work done during my Ph.D. experience. Since one of the goals was to develop a new piece of technology, the triangulation of different research approaches suggested by Mackay and Fayard seemed a reasonable solution for our design process (Mackay and Fayard, 1997). The studies run in the last four years have contributed to a better understanding of some aspects of this design which has undergone several cycles of refinement.

Among the four studies, two of them concerned pedagogical aspects of the design, whereas the other two dealt with HCI perspectives. In the former case, the investigation was driven by the observations gathered from the teachers who, whenever it was possible, participated in the design. Participants were recruited from carpentry classrooms during school hours and the experiments took place in their vocational schools. For the analysis both qualitative and quantitative data were gathered and combined.
The other two studies focused on the role of physical artefacts in the interaction, hence they were conducted as laboratory experiments. The hypotheses have been derived from the theories available in the literature and the investigations aimed at gathering empirical evidence that could support, question or refined them. In these studies, the results from quantitative analyses were preponderant.

The first three studies are characterized by the usage of an eye-tracking device to gather the position of participants' gaze during the experiments. The reader will notice to what extent this methodology offered a unique opportunity to complement the observations coming from other sources, like log files or questionnaires, and contributed to the interpretation of the results.
An extensive review of the contributions to the learning domain featuring the analysis of gaze movements could be found in (Mayer, 2010; Lai et al., 2013). Instead, the next section presents the terminology used in the next studies. The interpretations of variations in the gaze measures will be discussed in each chapter, since they depend on specific research questions.

2.3.2 Eye-Tracking Terminology

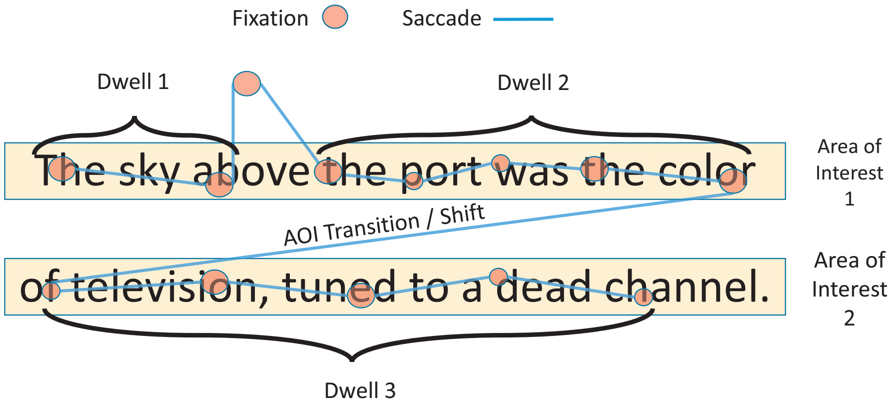


Figure 2.22 – Eye-Tracking Events (text from *Neuromancer*, William Gibson, 1984).

Fixations are eye events in which the gaze is stabilized over an area, typically lasting 150-600ms. Within a fixation, the gaze is not still but miniature movements take place as a consequence of the eye control system, namely tremors, drifts, and microsaccades.
A rapid movement to relocate the gaze on another point is called saccade, which has a duration of 10-100ms during which the person is effectively blind. Fixations and saccades provide the highest granularity to describe gaze behaviors[4], however they could be aggregated to create descriptions that might be more meaningful for specific analyses. For example, instead of considering the observed scene as a continuum, it could be discretized in zones that define areas of interest (AOI). Consecutive fixations on an AOI become a dwell, which is a unit that describes the period starting from the first fixation in the area and finishing with the last fixation on it. The features of a dwell derive from the properties of the saccades and the fixations contained in it, like the number of fixations or the sum of the fixation durations. For more details about the eye-tracking methodology the reader can consult (Holmqvist et al., 2011).

System Type : Video based glasses-type eye tracker

Sampling Rate : 30Hz binocular

Method : Dark pupil, pupil corneal reflection

Binocular Tracking : Yes (auto parallax correct)

Accuracy : 0.5 degrees over all distances

Gaze tracking range : 80° horizontal, 60° vertical

Frontal Camera Resolution : 1280x960

Figure 2.23 – SMI Eye Tracking Glasses specifications.

[4]In addition to fixations and saccades, other eye movements are reported in literature (e.g. smooth pursuit, vergence, vestibular, etc.). This events are typically not detected in commercial eye-trackers, hence I do not present them.

In all the experiments, participants wore the mobile eye tracking device *SMI Eye Tracking Glasses*, featuring binocular pupil tracking at 30Hz (Figure 2.23). The eye-tracking raw data were exported using the software *SMI BeGaze* and successively the gaze events were associated to the areas of interest defined in each experiment.

2.3.3 Pedagogical Framework

In the design of our technology we adopted a *constructive* stance, believing that the development of a qualitative understanding of statics requires to engage learners in rich sense-making activities. An intuitive knowledge of such topic requires to be constructed through active learning processes in the sense that "learner engages in appropriate cognitive processing during learning (e.g., selecting relevant incoming information, organizing it into a coherent mental structure, and integrating it with relevant prior knowledge)"(Mayer, 2009). Our technology is meant to be integrated in a pedagogical activity to support such appropriate cognitive processes. It does not prescribe a specific pedagogy and, as such, it can serve both active instructional methods, such as guided discovery or collaborative activities, and passive ones (e.g. principled presentations).

The studies presented in this thesis concerned discovery-based activities which we imagined to complement traditional class sessions. When we evaluated our design choices, an immediate learning outcome consisted in the evaluation of students' performance in statics problem solving exercises before, during and after a given activity. This kind of assessment allowed us to gain insights about learners' difficulties and common mistakes. However, since our learning objective could not be achieved through single interventions, our activities often did not lead to significant learning improvements.
Hence, the correctness of the students' solutions could not be the only desired outcome. We investigated also how the discovery was affected by the design variations, for example, in terms of similarity between novices and experts in solving statics problems or according to the quality of the verbalization of learners' reasoning. We have previously mentioned that an obstacle to the construction of a correct intuition of statics and, more broadly, physics is represented by the body of misconceptions built from everyday observations. Hence, a successful design would be one that challenges students' prior knowledge and help to identify analogies or crucial differences between case scenarios. Engaging learners in an exploratory activity makes them generate their own ways of framing problems, ideas, explanations and solutions. These productions would be often incorrect or suboptimal and they would lead to a unsuccessful attempt to solve the given problems. Nevertheless, the rationale for having such generative phase could be found in the *preparation for future learning* (PFL) principles(Bransford and Schwartz, 1999). According to the PFL framework, before introducing learners to the correct methods and solutions, students should engage in activities meant to stimulate their curiosity and to build a type of prior knowledge called perceptual differentiation. The term refers, for instance, to the ability of distinguishing meaningful details in the description of a problem from irrelevant features. Students develop this ability by analysing and comparing cases that

are carefully designed for such purpose (contrasting cases). These cases could be generated by the learners through an exploratory activity, but the important aspect is that learners eventually confront their productions with the canonical solutions (Schwartz and Martin, 2004; Kapur, 2008). In this way, learners can deeply appreciate such solutions and understand the issues that led to their formulation. The PFL framework has found application in the design of learning activities about statistics, physics and neuroscience(Schwartz and Martin, 2004; Schwartz et al., 2011; Schneider et al., 2013b). Recently Schneider has discussed the potential of mixed-reality technologies to implement technology-enhanced PFL sequences which leverage on the aforementioned learning benefits (support to spatial cognition, multiple representation, physicality, etc.) to scaffold the generation of hypotheses by the learners (Schneider, 2017).

We did not follow the PFL guidelines, since our activities were more open-ended than traditional PFL ones. Furthermore, due to practical constraints, the exploration was not followed by a phase of direct instruction. Even so, we have found in the PFL principles a constructivist-oriented way of assessing the potential of our AR-based learning tool. It could operate under the same assumptions: fostering learners' *intuitions* about statics in order to prepare them for what will be taught in a later stage.

3 Research Context

3.1 The Swiss Vocational Education System

The Swiss Vocational Education and Training (VET) provides education at upper-secondary level, enabling young people to enter the labour market and assuring that they gain the bases to become experts in the future.
Approximately two-thirds of all Swiss adolescents attend a vocational education program after finishing their ninth year of compulsory school and around 60.000 federal certificates are annually awarded (SERI). As in other German-speaking countries, most of the VET programs in Switzerland are based on the dual track approach in which apprentices generally spend part of the week in school and the rest in a company. The number of days allocated to the

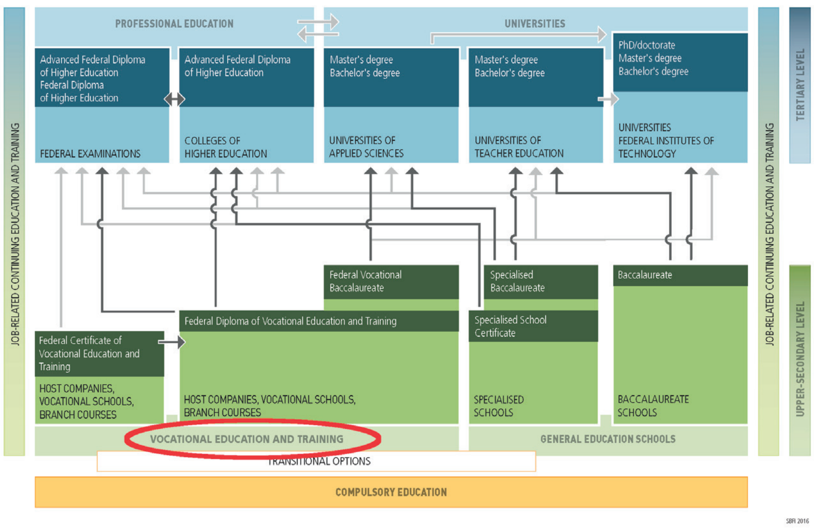


Figure 3.1 – The Swiss educational system and its possible paths.

two locations changes during the year of training, starting with a prevalence of school days in the first year and finishing with one day per week in school at the end of the training. School classes concern general subject matters (e.g. languages, mathematics) and theoretical aspects of the specific vocation (e.g. office skills), which are taught by teachers who usually have working experience in a company before becoming educators.
For the rest of the time the apprentices work in the company with which they have signed the apprenticeship contract. Apprentices are assigned to a supervisor who is usually a senior worker with a license for training young employees. The supervisor helps the apprentices to master the required competences in authentic situations. Within this context they acquire practical skills, learn a professional way of working, and actively take part in the host company's production processes.
The goals of the dual approach could be summarized in the following points:

- reducing the gap between the training programs and the needs of the labour market;
- developing professional competences that enable apprentices to manage current and future occupational requirements successfully;

3.1.1 School and Company: a Stormy Relationship

According to Eraut (Eraut, 2000), the knowledge acquired in school is predominantly explicit, declarative and theoretical, whereas workplace knowledge is mostly implicit and tacit knowledge contextualized in the specific practice. Learning in school is mainly based on formal and intentionally planned educational activities with a more general focus. In contrast, learning at work is mostly informal, encapsulated in the social context and it requires collaboration with other people.
The underlying hypothesis of the dual track system is that learners would be able to connect these two realities and to merge coherently the bodies of knowledge coming from the school and the workplace. The process should result in the development of *work process knowledge*, a type of "knowledge which arises from reflective work experience and is incorporated in practical work" (Rauner, 2007). Nevertheless, the weakness in VET is the observation that "although the school and the companies are supposed to work hand in hand, they do not have a great deal in common in terms of their aims, content or sociological organization. In view of this, the dual-track system can be viewed as requiring the learning of one profession from multiple contexts. The bundling together of knowledge, skills and attitudes acquired in these various contexts is incumbent on the apprentice her/himself" (Gurtner et al., 2012). Often apprentices know a lot but are not able to utilize this knowledge fully in the workplace, leading to a *skills gap* between workplace and school experiences (Schwendimann et al., 2015). For example, apprentices in logistics learn how to arrange the shelves in order to maximize the warehouse performance, but they rarely have the chance to apply this knowledge at the workplace. Similarly, carpentry apprentices spend most of the school time hand drawing, but in the company their role is usually to implement a given construction plan. Moreover,

depending on the company they are hired by, apprentices might have or not have the chance to make some experiences. For instance, a carpenter working for a company that manufactures timbers will never go to a construction site and place a scaffold.
The research presented in this thesis constitutes one direction of the Dual-T project (Dual-T), which aims at bridging the gaps between the multiple vocational contexts. Assuming that the differences between school and workplace are essential to the success of the dual model, the project considers the necessity of boundary crossing spaces to integrate what is learned in both places without trying to suppress their specificities. An aspect of the project is to investigate the features of learning technologies that could enable to bridge the gap between school and workplace, as well as between the stakeholders who belong to these locations. It also explores learning activities that are relevant to the contexts of vocational education and that could benefit from technology enhanced learning. The central hypothesis of Dual-T is that digital technologies can create a reflection space that connects workplace experience to classroom activities. This hypothesis is translated in the concept of the *Erfahrraum* (combining the German words experience and space), which describes multiple technologies and activities that create a shared space to foster learning through reflection. Through the systematic reflection of their experiences, apprentices integrate practical and theoretical knowledge. Thanks to the reflection space created by the *Erfahrraum* knowledge can be communicated back and forth from one context to another and shared with all actors (Schwendimann et al., 2015, Figure 3.2).

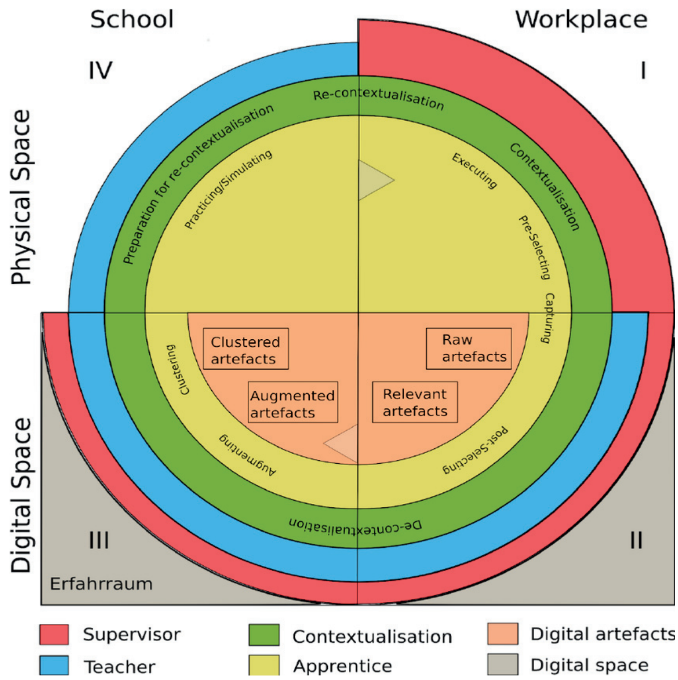


Figure 3.2 – *Erfahrraum*: a pedagogical model to inform the design of technology-enhanced VET learning activities (Schwendimann et al., 2015).

The implementation of the *Erfahrraum* principles could be found in the learning platform

Realto (Realto, Figure 3.3). Realto is an online platform with social features providing a digital space in which apprentices, teachers and supervisors can share resources and experiences. Apprentices can upload photos, videos and other media in order to bring their workplace experiences in the classroom, where they become material for the lessons. These entries can also be used to populate the learning journal, which is a personal record of the experiences made during the training and including the reflections on such experiences.
Teachers can group students according to different criteria (e.g. class, topic) and within these groups they can create classroom activities. For example, a carpentry teacher may ask apprentices to submit pictures of roof structures and annotate the different types of timber connections in them. In this way, teachers have the chance to contextualize the theoretical knowledge in the actual practice. The platform offers also a dashboard tool to monitor the status of the groups and of the activities.
Supervisors have their profiles linked to the ones of their apprentices, facilitating the communication between them. Supervisors can control and validate the learning journal entries suggesting modifications and improvements. They also ensure that the apprentices do not publish material that is protected by company restrictions.

The architecture of Realto allows third-party software to access and create resources too. In this way, applications running outside the web environment, like the augmented reality application developed during my research, can still store data on the platform. This becomes another form of experience that feeds the *Erfahrraum* space.

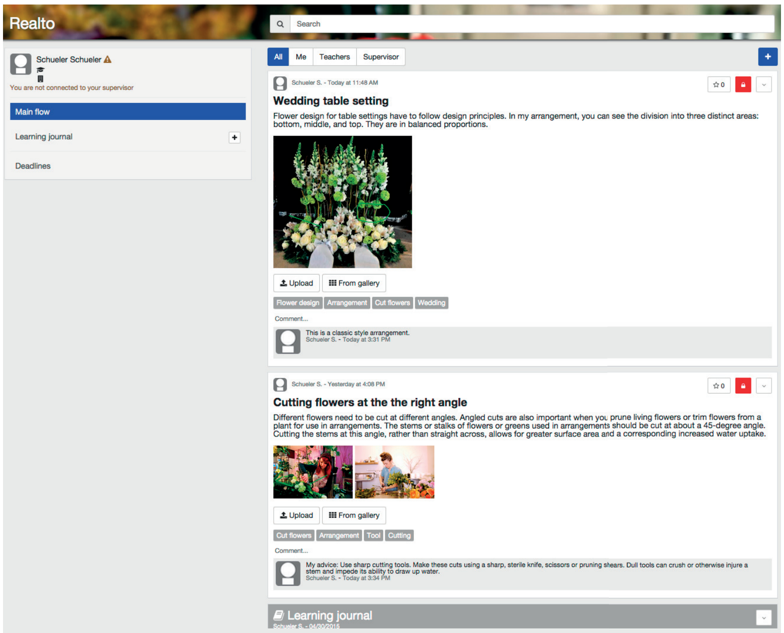


Figure 3.3 – Realto: online learning platform for vocational education (Realto).

3.2 Carpentry Training in Switzerland

Every year around 1500 adolescents decide to start their training in carpentry (Holzbau-Schweiz, a). The apprenticeship includes all the aspects related to timber construction, like acquiring drawing skills, learning the types of timber and how to store it, using machines, assemble pre-built structures and so on. The apprenticeship lasts 4 years after which about 15% of the students will continue to foreman programs while about 5% will attend *Berufsmittelschule* in order to later attend a university of applied sciences. Classes are composed by a maximum of 24 apprentices, all working in different companies (very few exceptions). In the school curriculum, about five hours per week are dedicated to carpentry related classes, including material and technology knowledge, drawing and arithmetics. In addition to the school and the workplace, apprentices attend inter-company courses for a total of 32 days. The goal of these courses is to develop the apprentices' practical skills supervised by a teacher while avoiding the pressure of a company environment.

3.2.1 The Role of Statics and Vocational Teachers' Experience

In chapter 1 we talked about the recent ordinance for the Swiss carpentry training (2014) that has extended the apprenticeship duration from 3 to 4 years and has increased the importance of statics in the curriculum (Holzbau-Schweiz, c). The study of statics and physics of structures features as part of the school program and it contributes to the development of apprentices' professional competences such as compiling a renovation report, manufacturing and erecting pre-built frames and trusses and installing the temporal bracing of a roof. The execution of these tasks is generally defined by instructions. For example, on construction sites carpenters are not supposed to make decisions based on their limited knowledge. That is the job of a master carpenter with a degree in construction science, of a structural engineer or of an architect. Carpenters receive information by the engineering office in form of a statics plan (Statikplan), which describes, for instance, the section for each beam, the nails or the type of bolts for the connections. Nevertheless, it is a shared opinion that apprentices should develop an intuitive understanding of statics to face the challenges that they daily encounter on the construction site. Even in case of constructing a new building by implementing the plan of an engineer or an architect, if carpenters do not realize the importance of some design choices, they could make mistakes and accidentally induce changes in the structural behavior (Frühwald and Thelandersson, 2008). Statics knowledge is fundamental to avoid these mistakes and this is one of the reasons that motived its introduction in the curriculum.

To our knowledge, there are few accessible studies in the international context about vocational research that have addressed the specificity of teaching statics (or more generally mechanics) in vocational classrooms (Rauner and Maclean, 2008, review). However, these studies were framed within the professional education and training (PET) which, in the Swiss system, takes place after apprentices have completed the apprenticeship. Due to this lack of documentation in the vocational education literature, we felt the need to collect the opinions and thoughts of several carpentry teachers before jumping in the implementation of any technology. Eight teachers from three different schools were willing to share their experiences about teaching this topic and explore new solutions. Considering that the adoption of 4-year apprenticeship has started in the fall semester of 2014 and that our research started around the same time, the observations that follow refer to teachers' experiences in the former 3-year curriculum.

Statics is typically introduced to apprentices together with the general topics related to mechanics and the strength of materials, such as mass, forces, lever or pulleys. These topics are covered in approximately 15 lessons (45 minutes each). In addition to the textbook, which often presents the topics in a theoretical and abstract way, teachers devote part of their time in creating practical examples and hand-on activities. For instance, a folding ruler in the shape of a portal frame is used to demonstrate the effects of sideways forces (e.g. wind); in order to show the effect of the gravity force on the members of a triangular truss, teachers make pairs of apprentices and ask them to lean forward and push off each other; the same exercise could be used to illustrate the action-reaction principle by putting soap under the shoes of one of the apprentices, who will slide sideways. "We are practitioners!" is the teachers' motto, marking the importance to show practical examples, to manipulate, to play, to try. The hands-on and embodied approach does not scale for presenting more advanced scenarios and it does not necessarily guarantee that apprentices would learn the new concepts.
The time spent on actual structural behavior is a small portion and it includes mostly examples of simple beam systems or trusses. These sessions are structured in three steps: (1) showing real-life scenarios, like the design of a new building, an example of failure, etc.; (2) the teacher demonstrates on the blackboard the important structural aspects and the procedures to compute forces, stress or correct dimensioning of the structure elements; (3) the students replicate the procedures using a worksheet.

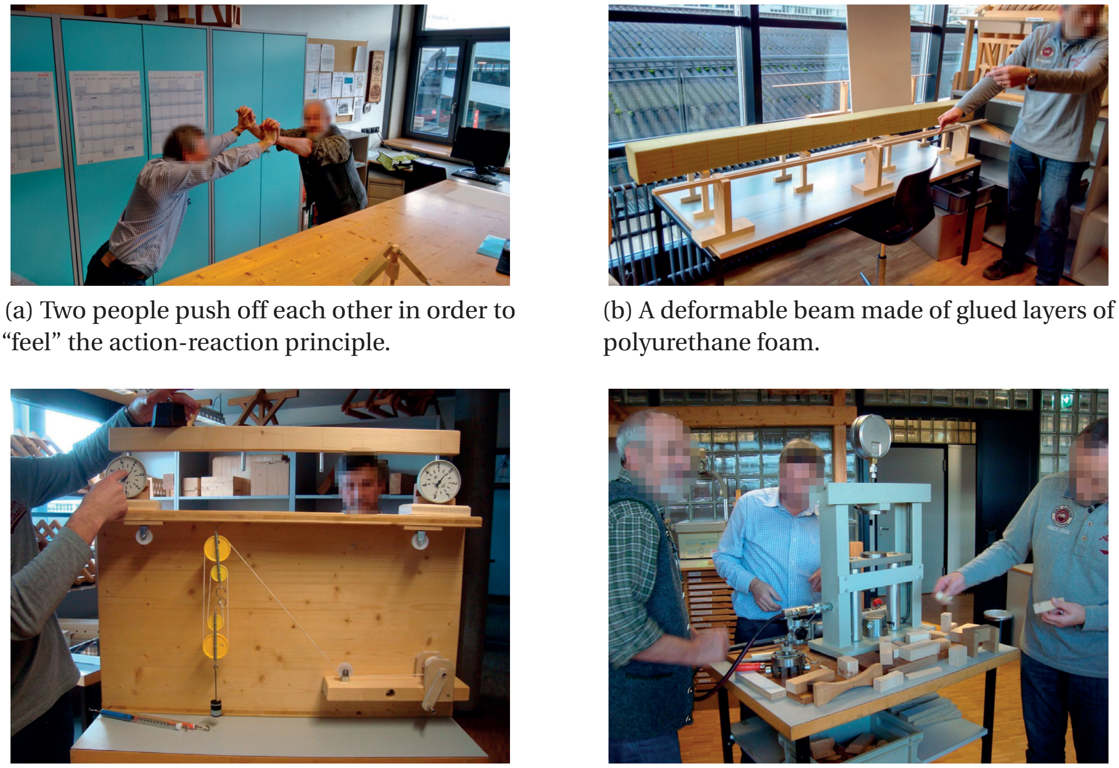
As regards the difficulties exhibited by apprentices, according to one of the teachers who has been lecturing foreman carpenters in advanced statics[1], carpenters who joined his courses had difficulties in visualizing how loads act on structures (converting individual loads to line-loads or area-loads) but also in making sense of the formulas for bending and deformation. The problem seems to arise from both the visualization skills needed to build mental models of these physical entities in 3D and the grounding of the subject in concrete workplace examples.

Hence, considering a long-term horizon, the acquisition of a conceptual understanding during the apprenticeship might be helpful to the carpenters who will seek for higher educational diplomas too.

The general domain constraints from the teachers can be summarized in the following points:

Avoid formalisms and present concrete examples The mathematical reasoning developed during the apprenticeship is generally oriented to the execution of the professional

[1]Advanced statics and quantitative methods are taught in professional courses after completing the apprenticeship. The course usually include 35-40 lessons about statics and structural analysis.



(a) Two people push off each other in order to "feel" the action-reaction principle.

(b) A deformable beam made of glued layers of polyurethane foam.

(c) A pulley system. On the top, a simple beam with two supports. The two load cells show how a load is distributed between the two supports.

(d) A small hydraulic press to test the strength of several materials.

Figure 3.4 – Activities and tools for introducing topics related to mechanics.

tasks. In class, teachers develop concrete problems in order to stimulate apprentices' explanations and solutions [2]. In this way, there would be higher chances for students to recall intuitions they might have had while working.

Minimize the downtime Time is a scarce resource in vocational schools. The materials for the course are ready to be used and generally available in the classroom or in a storage room literally distant a couple of minutes from the class. This means that, for example, a physical model has to be quickly assembled/disassembled because teachers only need it briefly and then store it away. Teachers showed a positive attitude towards having an AR application running on the students smart-phones since it would not require to move the class to a computer lab.

Design for physical robustness Physical and bodily interactions are at the core of the carpentry learning experience. Students are surrounded by models that they can dismantle, manipulate and test. This requires physical prototypes and products to be sturdy.

[2] Similar observations were made by Millroy in (Millroy, 1991).

3.2.2 Carpentry Structures: a Brief Introduction to Trusses and Frames

Truss structures are usually encountered by apprentices when working on the construction site, especially in the form of timber roof trusses. Trusses are modelled as assemblies of bars that are joined at the two extremities by pin connections (joints). The model assumes that the connections do not transmit any momentum and the external forces can be applied only at the joints, hence the elements of the trusses can only be subjected to tension, compression or zero forces. Zero-force members have usually the goal of increasing the stability of the structure. In addition, the load due to self-weight is neglected. Some of the joints are restrained to guarantee support to the structure. The supports can be either *pinned*, which offer restrain on translations, or *roller*, which provide horizontal (or vertical) reaction forces. Depending on the configuration of members and supports, a truss can be unstable, statically determinate, and indeterminate. For statically determinate trusses, the forces in the bars can be calculated using only the equations of static equilibrium. However, this is not possible for indeterminate structures due to the presence of redundant supports or elements, thus requiring additional equations. In the studies ran during my Ph.D., the structures were mostly statically determinate.

Unlike trusses, a frame is a structure having at least one multi-force member. The connections can be either pinned or welded, in which case the momentum is propagated between adjacent members. The members are subjected to shear and bending forces in addition to the axial one, thus the analysis of frames takes into account also the cross-section of the beams and their deformations. In addition to pinned and rolled supports, in the frame some joints can be fixed, meaning that they provide a reaction against vertical and horizontal forces as well as a moment.

There are several methods to analyze determinate trusses, some of which are numerical (e.g. method of the joints) or graphical (e.g. Cremona diagrams). For general frames, the handwritten analysis is limited to simple structures like beam systems or portals, whereas for more complex structures computer aided tools are preferred (Muttoni, 2011).

Figure 3.5 – A scissors truss (*credits: Montana Reclaimed Lumber Co*).

Figure 3.6 – An example of frame: EPFL ArtLab (*credits: espazium.ch*).

3.3 Conclusions

This chapter aimed at outlining the Swiss Vocational Education and Training system and the characteristics and limitations of the dual-track apprenticeship. Furthermore, it illustrated the vision of the research project Dual-T, which has proposed to overcome the gaps between school curricula and workplace practices by creating digital spaces where the bridging between them is made possible: the *Erfahrraum*.

Additionally, the carpentry training was explained together with the role of statics in this profession. In such a context, a qualitative understanding of statics is considered a professional competence and apprentices should be able to apply this knowledge to the situations they come across at the workplace.

4 Study I: TUI Benefits through the Eye-Tracking Lens

4.1 Introduction

In this chapter we present an eye-tracking study which aimed at comparing the effects of TUI and GUI when solving a task involving spatial reasoning. Chronologically, the theme of statics in carpentry training emerged towards the end of this study. This broadened the study of Cuendet about using tangible interfaces for enhancing carpenters' spatial skills (Cuendet, 2013). Nevertheless, this work is not disconnected from the rest of our research, since it treated a central subject of this thesis: the impact of physical artefacts in mixed-reality experiences.

As discussed in chapter 3, several authors have shown that TUIs are better suited to support the users' spatial reasoning compared to GUIs. The putative benefits are based on the hypothesis that the physicality of the tools scaffolds the process of building mental models of the entities that the users manipulate and of their spatial relationships (Marshall, 2007). Moreover, a tangible representation is supposed to provide an intermediate level of abstraction between real objects and their representations on the screen (Zufferey et al., 2009).
I use the term "putative" because there is still an on-going discussion in the TUI research community about the lack of empirical studies that could support the aforementioned hypotheses and about the development of a theoretically grounded framework that could account for those benefits (Antle and Wise, 2013).
To our knowledge, at the time this study was run, in 2014, the application of the eye-tracking methodology to TUI research was novel, although it was already widespread in other HCI research fields. The eye-tracking literature encompasses a variety of theories that link the differences in users' mental processes with variations at gaze level. Hence we decided to investigate the differences (if any) that arise in users' gaze behaviour when using either TUIs or GUIs. We designed the following comparative study in which we asked participants to perform a Computer Aided Design (CAD) activity with either a tangible or a graphical interface. Due to a lack of previous works combining gaze analysis and tangible interfaces, we were not sure which gaze variables would have exhibited a difference between the two interaction styles. This motivated the exploratory nature of the work that is presented in this chapter. The study

was mainly articulated around the following questions:

Q$_{SC}$ When comparing TUI and GUI which differences emerge at gaze level? How are they related to the supposed role played by TUIs in helping spatial cognition?

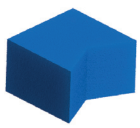
In addition to these questions, the experimental task allowed us to investigate a precise design dimension which is related to the matching between the physical shape of the tangibles and their digital representations, namely the physical correspondence. Physical correspondence was introduced by Price and colleagues in their framework as a dichotomous attribute for describing TUIs (Price et al., 2009). The authors distinguished between *symbolic*, describing the tangibles in which the digital entities share little or no characteristics with the physical ones, and *literal*, denoting the tangibles characterized by similar appearance between physical and digital counterparts. For our study we were inspired by the work of Cuendet, who studied the impact of the physical representation on users' performance (Cuendet et al., 2012a). The experimental task consisted in identifying some features of a digital 3D object across its orthographic projections. The author found that the number of mistakes decreased when the tangibles were in literal correspondence rather than symbolic. The findings were attributed to the fact that the users could look directly at the physical object and readily retrieve the spatial relationships necessary to correctly achieve the task.
Tangible interfaces often lack the property of being mutable, especially when it comes to re-modelling the physical representation after the digital one. For instance, in a subtractive modelling activity an immutable tangible interface will lose the initial literal correspondence over time. In (Ishii, 2008), Ishii described the interaction with a TUI as composed by three feedback loops: (1) the passive haptic feedback loop, which is generated when users sense the actual interface. This loop happens in the physical domain and does not require any digital mediation; (2) the digital feedback loop, which corresponds to the update of the digital information according to a change of the physical entity, such as a movement; (3) the actuation loop through which the physical representation gets updated according to the digital state. This third loop is rarely enabled, since it requires embedding actuators in the physical objects in order to reflect the updates of the digital model (Coelho and Maes, 2008; Ishii et al., 2012; Özgür et al., 2017). What happens when the loop cannot be implemented and the literal correspondence between the digital and physical models is lost? We hypothesised that the spatial support offered by TUIs might vanish, hence the users would end up in overlooking the tangible object. We called this transition "tokenization": the geometrical properties of the TUI do not get mapped to properties of the digital entity anymore and the physical/digital mapping now depends only on the three physical proprieties of presence, position and proximity (Ullmer et al., 2003). The TUI turns to be used as a mouse. In order to confirm our hypothesis, the second point we investigated was

Q$_{Token}$ When the physical-virtual correspondence changes during the task, does a tangible interface become just a control "token"?

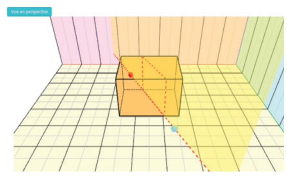
4.2 Experimental Setup

4.2.1 The Cutting Activity: a CAD Task to Train Carpenters' Spatial Abilities

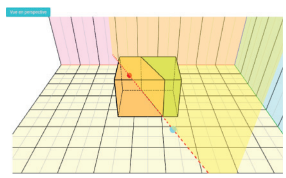
The experimental task employed in this study was the *cutting activity*. It consisted in a CAD activity in which the goal was to shape a 3D object according to a given target model (Figure 4.1). Starting from a cuboid block, the block got shaped through a sequence of cutting actions which split the object into fragments. Each fragment could be either deleted or kept in order to achieve more complex shapes by performing successive cuts. A demo video is available at the project page.
The activity was tailored to be used by carpentry apprentices, hence it combined the typical carpentry cutting practices (e.g. creating joints) with the creative thinking and deep spatial cognition necessary to define wooden mechanical puzzles.



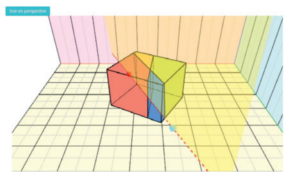
(a) Target Shape



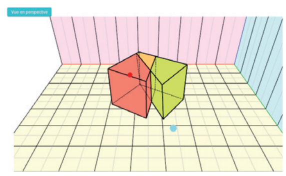
(b) Placing the cutting plane



(c) Perform the first cut



(d) Perform the second cut



(e) Select one fragment and remove it

Figure 4.1 – Example of a partial execution of the cutting activity.

4.2.2 Experimental Conditions and Implementation

The activity was implemented on e-TapaCarp, a web application providing exercises for training spatial abilities developed by Cuendet (Cuendet, 2013, chapter 8). The application runs TUI-based activities, for which it requires a camera pointing at a paper-printed workspace defining the area where the tangible tools are active and detected (Figure 4.2). The detection is performed by means of Chilitags fiducial markers, a JavaScript library for the detection of plain squared markers (Bonnard et al., 2013).

The study presented two experimental conditions: *tangible* and *virtual*.
In both experimental conditions, the participant received the target shape as a styrofoam object. On the screen, the scene was rendered from a perspective camera having a fixed position. A cuboid block – the object to be cut – was arranged on a grid (Figure 4.1b). The

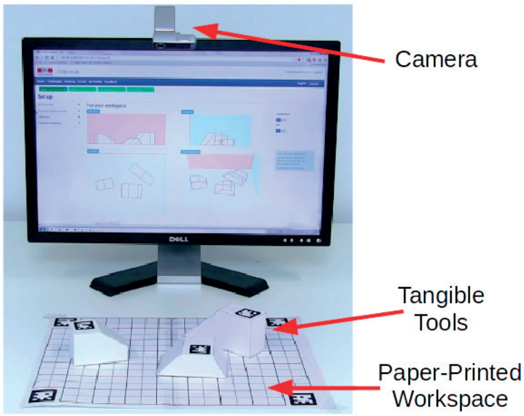


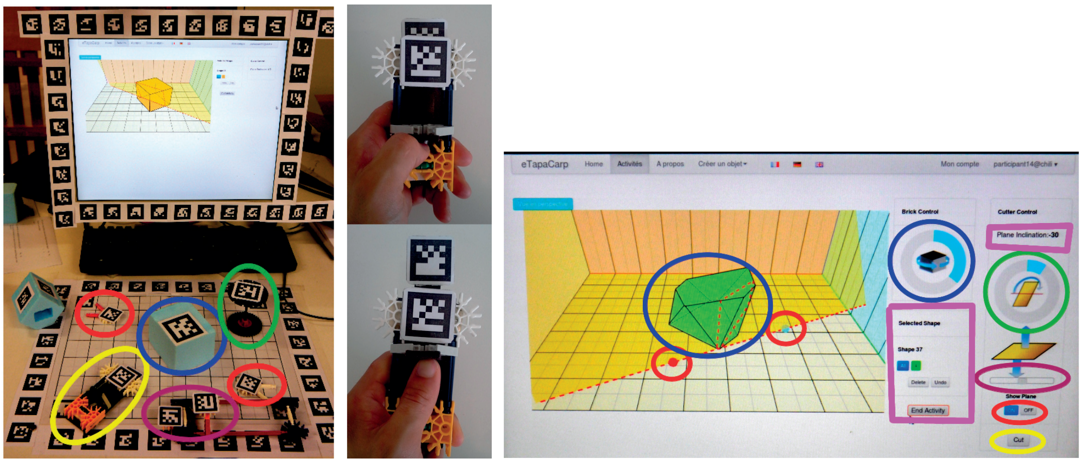
Figure 4.2 – E-TapaCarp setup for running TUI-based activities.

block could only be moved within the grid and could only be rotated along its vertical axis. The displayed grid represented the digital counterpart of the paper-printed workspace taped on the table in front of the participants. Both the digital grid and the paper-printed workspace were the only measurement tools available during the task, and one square unit on the former corresponded to one square unit on the latter (15 mm x 15 mm).
The cutting tool was depicted on the screen as a semi-transparent plane. It could be moved on the grid, tilted or flipped in horizontal position, allowing the users to perform cuts at different angles and heights. As shown in Figure 4.1, after validating a cut the plane split the block into two or more fragments. Fragments were coloured randomly in order to easily select and delete them. Both the cutting and the deleting actions were reversible.

Figure 4.3a shows the implementation of the activity for the tangible condition. On the paper-printed workspace, the styrofoam cuboid in the blue circle was used to control the block on the screen (H: 60mm, W:90mm, L:75mm). At the beginning of the task, the physical shape and the digital one were the same, but, as the task progressed, the correspondence became less and less literal. The elements in red circles defined the ground line of the plane, which was visible on the screen only when both markers were detected. At construction time, the plane was set perpendicular to the grid, passing through the ground line. The wheel in the green circle allowed the users to tilt the plane between -90 and 90 degrees. When the plane reached the horizontal position, the slider highlighted in violet could be used to change the plane elevation. Finally, the tool in yellow acted as a switch-blade and triggered the cuts (detailed view in Figure 4.3b).

In the virtual condition, the tools were replaced with graphical counterparts on the screen and were controlled with the mouse (Figure 4.3c). Participants did not receive the styrofoam block, but they could drag and drop the digital block on the workspace using the mouse, whereas the rotation was performed through a knob interface (the blue circles). The two markers defining the plane line were replaced by the two spheres in red circles, which were draggable as well.

The knob in green and the slider in violet were implementing respectively the functionalities of the wheel for tilting and the slider for changing the elevation. The switch-blade had been replaced by a button.
The only graphical elements shared between the two implementation were a set of coloured buttons to select the fragments, a text field containing the current tilt angle of the plane, and two buttons to delete a fragment and to undo the last action (Figure 4.3c fuchsia squares).



(a) Tangible Setup (b) The switch-blade tool (c) Virtual Setup

Figure 4.3 – The two interfaces. Same color corresponds same function in both implementations.

The fiducial markers surrounding the screen and the workplace did not implement any functionality, they only provided landmarks to automatise the analysis of the eye-tracking data.

4.2.3 Participants and Procedure

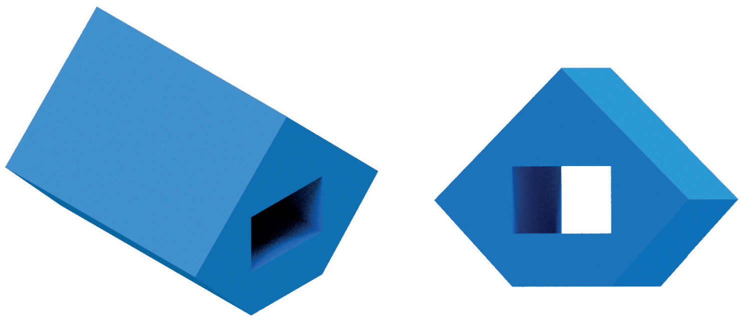
Eighteen undergraduate students took part in the experiment, 16 males and 2 females, from 2nd to 4th academic year, 7 Mechanical Engineers and 11 Micro-technique engineers. They had a prior knowledge of the 3D modelling and CAD software thanks to their academical curricula. They were asked to fill a questionnaire in order to collect their demographic data, including skill level in using CAD software or habit of playing 3D video-games.
Before starting the experimental task, participants took the Vandenberg and Kuse's Mental Rotation Test (MRT) and the Paper Folding Test (PFT) for the purpose of estimating their spatial skills. The MRT included 12 questions, each question having two correct answers that participants had to mark to get one point. The PFT included 10 questions with only one correct answer per question. The time limit for each test was 3 minutes. Both the questionnaire and the Paper Folding Test test are available in Appendix A. The Mental Rotation Test cannot be publicly published.

Each participant was randomly assigned to one of the two experimental conditions. The experimental task included 3 parts:

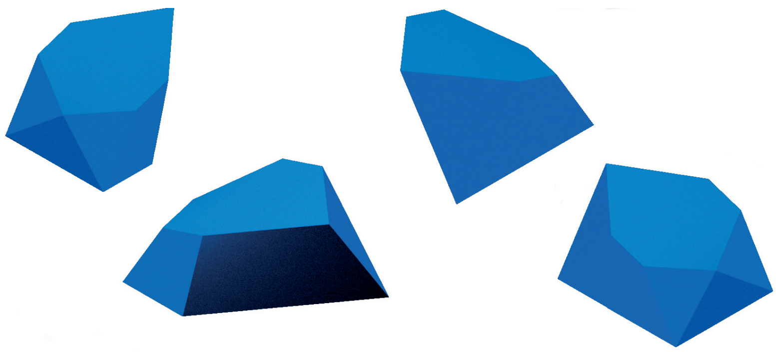
Demo At the beginning, we explained the cutting activity through a demo session in order to get acquainted with the system. No time limit was set for the demo, hence the next trial started only when the participant felt ready.

Trial 1 In trial 1, the target shape was symmetrical (Figure 4.4a). The minimum number of cuts required to achieve it was 6 which produced 10 fragments.

Trial 2 In trial 2, the target shape was asymmetrical (Figure 4.4b). The minimum number of cuts required to achieve it was 5 which produced 5 fragments.



(a) Trial 1. Axis-Aligned Bounding box H: 65, L:80, W:75



(b) Trial 2. Axis-Aligned Bounding box H: 70, L:120, W:90

Figure 4.4 – Styrofoam models.

From a pilot study the second shape was found to be more difficult than the first one, although it required fewer cuts. The main challenge derived from the absence of symmetry, which required the precise estimation of the cutting angles. Moreover, its bounding box was larger then the physical block, thus participants in tangible could not be facilitated in estimating the right proportions by overlapping the block with the target model.
During the whole execution the participants were wearing the mobile eye tracking device. At the end of the experiment, a short interview about the experience was conducted.

4.3 Statistical Analysis and Findings

We used the software R v3.0.2 for the statistical analysis, employing ANOVAs on linear models or, whenever this was not possible, non-parametric tests. Repetitions were taken into account using mixed effect models implemented in the *lme4* R package (Bates et al., 2015).
The analysis excluded two participants (both females) from our population as they represented outliers in the distributions of the duration.

4.3.1 User Performance and Action Analysis

Pretest Scores The median scores for the mental rotation and paper folding pretests were respectively 9.75 (interquartile range: 4.75) and 9 (interquartile range: 1.75), indicating highly developed spatial skills. The comparison of the scores between the experimental conditions did not show any significant difference, hence no bias was present between the two groups (MRT: $W = 40.5$, $p = 1.0$; PFT: $W = 38.5$, $p = 0.89$). In general, we did not observe any meaningful variation attributable to the pretest scores among the variables taken into account for this study.

Quality of the Outcomes The quality of the solutions produced by the participants has been assessed by asking five raters to give a score between 1 and 4: (1) the shape was completely different from the model; (2) one major mistake, but the target shape was still recognized; (3) the shape was mostly correct, really minor mistakes; (4) correct shape. The inter-rater reliability was 0.93.
The solutions for trial 1 were mostly correct with an average score above 3, while for trial 2 the average score was 2.6 (Table 4.1). No significant difference was observed in the quality of the final solution between the two experimental conditions.

Table 4.1 – Average quality scores.

	Trial 1	Trial 2
Tangible	3.05 (*SD* 0.63)	2.65 (*SD* 0.52)
Virtual	3.08 (*SD* 0.83)	2.67 (*SD* 1.16)

Time Performance The time to accomplish the tasks was slightly higher for the tangible conditions, in which participants took around 2 extra minutes compared to the virtual setup in both trials, although the difference was not significant (for trial 1 $F[1,14] = 2.48$, $p = .13$, for trial 2 $F[1,14] = 1.08$, $p = .31$).
By considering the time before the first cut for trial 1, the one-way test revealed that participants in the tangible condition performed the first cut earlier compared to the ones in virtual condition. More precisely, the first cut was performed on average after 51 seconds (SD: 13 s)

using the TUI, whereas it happened after 1 minute and 6 seconds (SD: 14 s) using the mouse. The difference between the two conditions was statistically significant only in the first trial ($F[1,14] = 4.33,\ p = .05$).

Table 4.2 – Average duration.

	Trial 1	Trial 2
Tangible	8 min and 16 s	9 min and 42 s
	(*SD* 3 min and 8 s)	(*SD* 3 min)
Virtual	6 min and 7 s	8 min an 6 s
	(*SD* 2 min and 10 s)	(*SD* 3 min and 8 s)

Fragments Created The median number of cuts performed by the participants when using either the tangible or the graphical interface was respectively 9.5 and 8.5 for trial 1, whereas 7 cuts and 6 cuts for trial 2. Although the number of cuts, deletions and undo actions did not differ between the condition, surprisingly a significant difference arose in terms of number of fragments created during the trials. As shown in Figure 4.5, in trial 1 the group using tangible interface created on average 21 fragments compared to the 13 created using the graphical interface. Similarly, in trial 2 the averages were 10 for the tangible condition and 6 for the virtual condition (for trial 1 one-way *Welch's* F[1,9.26]=7.13,p=.02, for trial 2 F[1,14]=5.03,p=.04). The result indicated that participants in the TUI condition preferred to delete the fragments towards the end of the activity, whereas participants in the GUI condition tended to delete them right after a cut. In the discussion section, such difference will be related to the loss of physical-digital coupling.

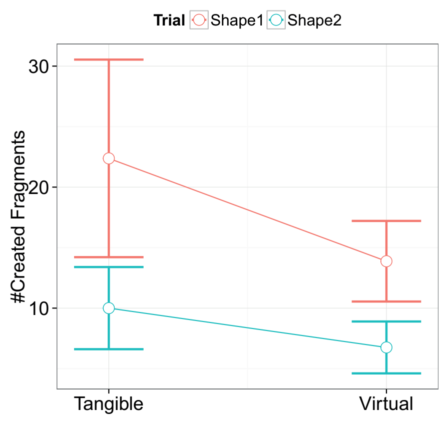


Figure 4.5 – Number of fragments created.

4.3.2 Gaze Analysis

Regarding the eye-tracking terminology, the reader can consult subsection 2.3.2. The fixations were associated to the related areas of interest and aligned with the user action logs. The analysis encompassed three of the most popular eye-tracking metrics: dwell percentage on the interface areas, average dwell duration and transitions among the elements of the interface. Dwell percentage is generally associated with the importance of the area, whereas the average dwell duration indicates difficulties in extracting information, usually during memorisation tasks (Henderson, 2003). Transition graphs and adjacency matrices are useful to identify coupled areas and visualise, to some extent, temporal dynamics.

In the next sections we will use the following abbreviations for the areas of interest (AOIs) shown in Figure 4.6:

- *ScreenOBJ* indicates the virtual object displayed on the left part of the screen and the area around it;
- *Block* denotes the styrofoam control block available only in the tangible setup;
- *Shape* refers to the target styrofoam objects;
- *ScreenGUI* refers to the right part of the screen containing the graphical interfaces. In the tangible setup it contained only the buttons to select the fragments and delete them, the undo button and a label showing the current tilt angle of the plane. In the virtual setup, this area included also all the graphical control elements to rotate the block, change the elevation of the plane etc., as previously mentioned;
- *Workspace* refers to the paper-printed workspace and it included the active tangible tools (e.g. rotating wheel, slider). Even though the paper-printed workspace was present both in the virtual and in the tangible condition, the area of interest has been defined only for the tangible one, since in virtual condition the user had no other object on the grid than the target shape. Hence, fixations at the workspace have been included in the *Shape* area.
- *Out* refers to everything not covered by the other areas. This area contained the mouse and sometimes the tangible tools not in use;

Block, *Shape* and *ScreenOBJ* form the set of the representation-AOIs, since they embed spatial information of the object the participants were working on, in contrast with the other areas that contained only controls.

Dwell Proportion on the Representation-AOIs Figure 4.7 shows the overall partition of the dwells belonging to the representation-AOIs. The average percentage of dwells on the tangible block constitutes a non-negligible amount in both trials. It is evident that there

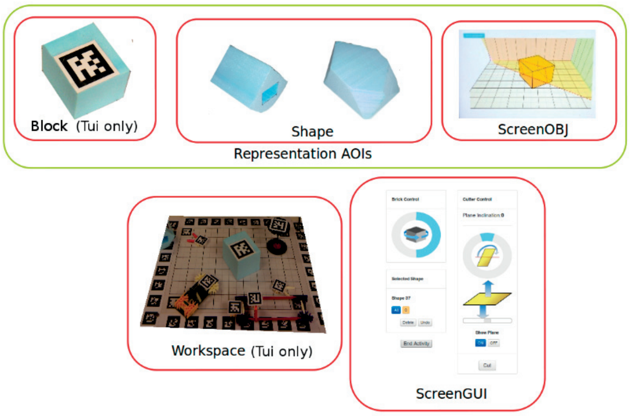


Figure 4.6 – Areas of interest.

was no statistical difference in the average percentages on *ScreenOBJ* area between the two conditions, thus the visual attention to *Block* seemed to be drawn from *Shape*. Participants who used the TUI allocated lower percentage of visual attention towards *Shape* compared to those using the GUI (for Trial 1 $W = 12$, $p = .04$, for Trial 2 $W = 13$, $p = .05$). The percentages of dwells on the *Workspace*, *ScreenGUI* and *Out* areas has been omitted, since they did not vary significantly between the two conditions. This could be interpreted as an indicator of the homogeneity of the two interfaces, in the sense that there was no considerable penalty in the adoption of either the tangible control tools or their virtual counterparts.

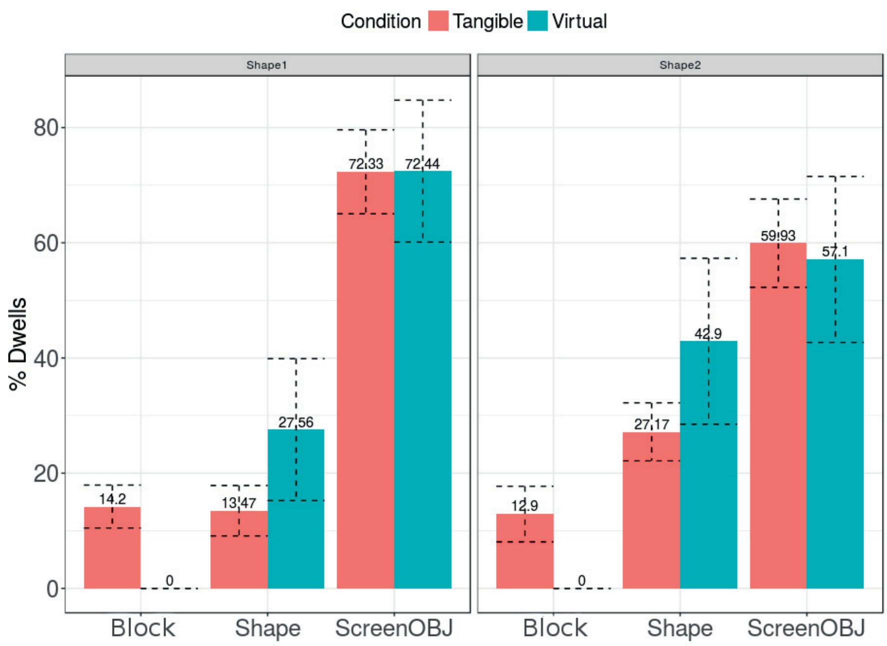


Figure 4.7 – Proportions of dwells for each representation-AOI.

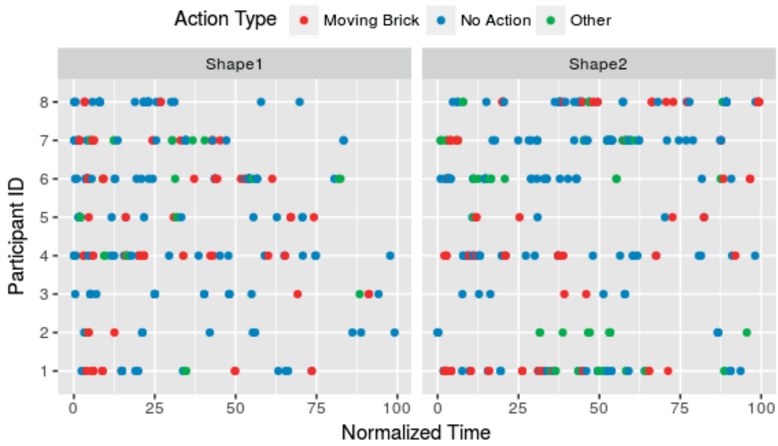


Figure 4.8 – Percentages of UI events happening while the users are looking at the block.

Gaze on the Control Block The visual references to the control block (coloured dots in Figure 4.8) appeared to be almost evenly distributed throughout the whole execution for both the trials. When we examined the actions performed during such events, it was interesting to notice that those fixations happened mainly when participants were not interacting with the system rather than while manipulating the block or the other elements of the interface. The "No Action" label included the highest percentages of fixations in both trials, respectively 65.75% (SD: 13.92) and 58.5% (SD:17.10). The difference with both the labels "Moving Block" and "Other"[1] is significant in both trials (trial 1 $F[2,24] = 56.96$, $p < .01$, trial 2 $F[2,24] = 13.15$, $p < .01$), which made us reject the hypothesis that the block acted as a mere controlling device. No difference in the average dwell duration was found between the two trials.

Differences in the Dwell Length for the Target Shape Participants in tangible condition had on average shorter dwells towards the target shape compared to those in virtual condition (Table 4.3). By building a mixed model using the participant's ID as grouping factor, the model showed an increment of 130ms in the average dwell duration for the virtual group. The difference was even more visible by restricting the analysis to the time windows when the participant was not performing any action. The intercept of the model increased by 150ms as a result of more mentally demanding tasks such as analysing the shape or planning the next actions. During these moments, the increment of the dwell length due to the virtual condition was 400ms. Regarding the two trials, the duration was found to be 100ms longer in the second one which was considered to be more difficult, although the difference was not significant.

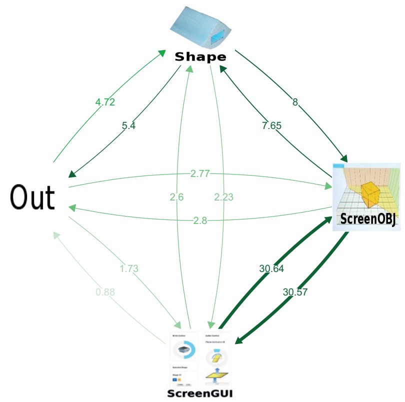
Transition among the AOIs An overview of the transitions among AOIs is shown in Figure 4.9. On each direct edge is reported the average percentage of transitions between the two areas over the total transitions. As expected, the transitions between *ScreenOBJ* and *ScreenGUI* characterised the virtual condition, since all the tools were located on the screen. These

[1]The label "Other" includes all the remaining actions like cutting, selecting a fragment, etc.

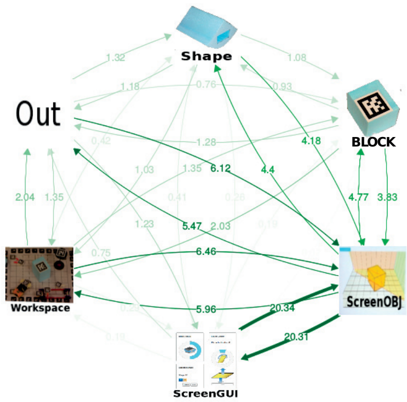
Table 4.3 – Average dwell duration on the target shape.

	Overall Task	No Action Moments
Tangible	324 ms (SE:36)	493 ms (SE:66)
Virtual	461 ms (SE:76)	886 ms (SE:174)
	$\chi^2(1)$=5.17, p=0.02	$\chi^2(1)$=8.96, p=0.003

transitions played an important role also in tangible condition during trial 1, as shown in Figure 4.9b. Similarly to the results on the percentage of dwells, in trial 1 (Figure 4.9a and 4.9b) the transitions between *ScreenOBJ* and *Shape* of the virtual condition have been split almost equally among the three representation-AOIs in the tangible setup. The same effect did not emerge so clearly in trial 2 (Figure 4.9d and 4.9e), where the transitions on the *Block* were less prevalent, mainly due to the *Out* area, which absorbed most of them.
Tables 4.9c and 4.9f show the average percentages of transitions between the representation-AOIs for the tangible setup. We noticed a *ScreenOBJ* centric distribution and an equal distribution of transitions between *Block* - *ScreenOBJ* and *Shape* - *ScreenOBJ* for trial 1. However, in trial 2 the transitions toward the *Block* account only for the 25,36% (SD: 13.70%), which was still an interesting proportion, but definitely smaller than the one towards the *Shape* (62,04% SD: 18.54%). The transitions between *Block* and *Shape* amounted to only a small percentage of the total transitions in both trial 1 and trial 2, respectively 10.42% (SD: 9.67%) and 12.59% (SD: 9.48%).



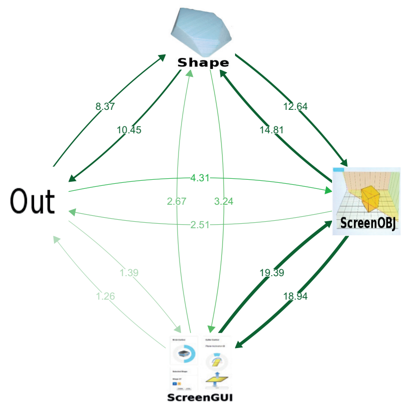
(a) Trial 1: Virtual Condition



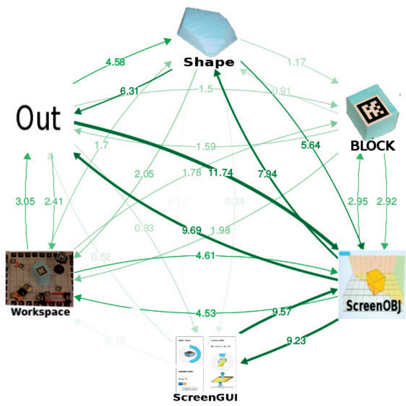
(b) Trial 1: Tangible Condition

	Shape	Block	ScreenOBJ
Shape	.	5.72 (SD: 4.37)	21.49 (SD: 6.18)
Block	4.7 (SD: 5.71)	.	19.72 (SD: 8.65)
ScreenOBJ	22.7 (SD: 6.59)	25.67 (SD: 7.69)	.

(c) Trial 1: Transitions among representation-AOIs in the tangible condition



(d) Trial 2: Virtual Condition



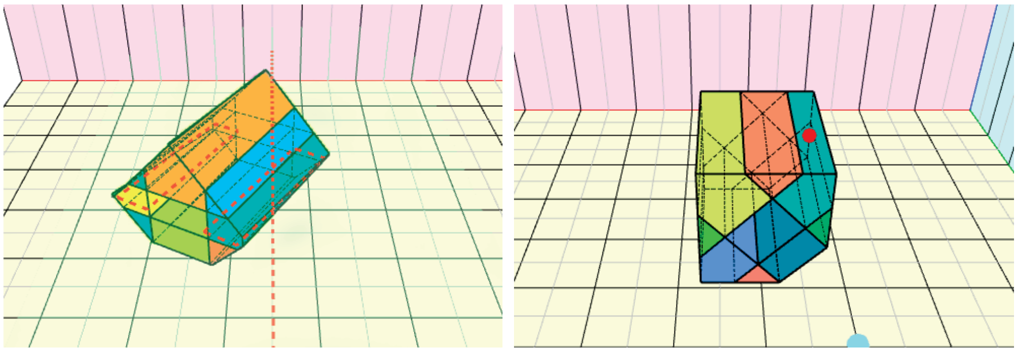
(e) Trial 2: Tangible Condition

	Shape	Block	ScreenOBJ
Shape	.	6.41 (SD: 5.72)	26.38 (SD: 10)
Block	6.18 (SD: 5.88)	.	12.47 (SD: 7.84)
ScreenOBJ	35.67 (SD: 12.03)	12.89 (SD: 6.11)	.

(f) Trial 2: Transitions among representation-AOIs in the tangible condition

Figure 4.9 – Transitions among the AOIs.

4.3.3 Findings from the Interviews



(a) Popular Solution (b) Optimal Solution

Figure 4.10 – The two possible approaches for creating the shape 1.

The majority of participants agreed on saying that shape 1 was easier to create than shape 2. The symmetry and the proportion of the sizes of the edges provided a reference which made clear how to set up the cutting tool. Shape 2, characterised by an irregular silhouette, led participants to frustration, since they were forced to come up with a solution which was perceived to be quite rough.

The main strategy to perform the cuts was to keep the plane fixed to the workspace during the task and then to move the block inside. This strategy was adopted by 13 out of 18 participants who gave mainly two justifications: (1) it is a legacy from the use of CAD software (e.g. Catia™); (2) moving only the block rather than the two controls of the plane was easier and resulted in more precise cuts. Moreover, in the tangible setup participants tended to occlude the two fiducial markers while moving the plane, which was disappearing on the screen.

As we said in the setup description, the point of view of the scene on the screen was fixed. It was a shared opinion that controlling the camera position would have improved the precision in cutting, since it would have made possible to check overlaps and intersections between the plane and the block. The current setting was mainly penalising the users in virtual condition. While in the tangible condition the concreteness of the block allowed to have a clear idea of the shape and to interpret readily the construction lines, the graphical interface demanded more manipulation to gain the mastery. The majority of the participants reported that they had to rotate the block several times before getting the feeling of depth between the edges and to realise that the initial block was not squared. This factor might explain why, before performing the first cut, the participants took less time for shape 1 in the tangible condition than in the virtual one.

The last observation was that only four participants, belonging to the virtual condition, carried out the solution for shape 1 which required the minimal number of cuts, consisting in tilting it on the side (Figure 4.10). Recalling that in our setup the block could not be freely manipulated in 3D but only rotated around the vertical axis, this design feature might have negatively influenced the search of a solution to only a subset of the possible ones. Even though the number is too small to get any conclusion, the effect might have been larger in the tangible condition in which the presence of the tangible block could have limited the identification of alternative representations and, consequently, the deeper exploitation of the mental rotation ability.

4.4 Discussion

Q$_{SC}$ When comparing TUI and GUI which differences emerge at gaze level? How are they related to the supposed role played by TUIs in helping spatial cognition?

The lower percentage of dwells on the *Shape* area in the tangible condition compared to the virtual one was related to a partial shift of the visual attention towards the physical block. The role of the block went beyond that of physical control. Participants were referring to it mainly during the intervals when no action was performed, which were likely to be moments while they were reasoning about the task or evaluating the current status. Neither the percentage of dwells on the block nor their average duration were affected by the trial, thus we could assume that looking at the block did not depend on the difficulty of the task, but it rather responded to the users' periodic needs for perceptual cues. The needs were coming mostly from the ambiguity of the digital scene. From the transition graphs it could be noticed that the transitions between *Block* and *Shape* in TUI were quite rare, whereas the centrality of the *ScreenOBJ* emerged. The perceptual benefit associated to the block would arise from the direct alignment between the physical and digital realms, which provided a bridge between these two spaces. What the users perceived in the physical world was also mapped in the digital one. Thus, **the TUI eased the extraction of spatial information perceived through both eyes and hands** (Marshall, 2007). In the pure GUI condition, spatial properties were provided through artefacts (e.g. depth was obtained using dashed lines), which required the additional cognitive step of decoding the order of surfaces and lines from their rendered properties.
We would have expected more *Block*-*Shape* transitions in the first trial, since the target shape could be inscribed in the block, whereas in the second trial there was no benefit in directly comparing the two objects due to the target shape being larger than the block. However, no difference emerged. This suggested that the two areas, *Block* and *Shape*, appeared to be perceived as diametrically opposed stages of the task, respectively the initial state and the final one. Also the transitions between them were mostly passing through the current task state, which was given by the *ScreenOBJ* area.
Another variation between the two experimental conditions was found in the average dwell duration for the *Shape* area. Recalling the interpretation of this metrics from the eye-tracking literature, the shorter dwells in the tangible condition revealed less difficulty in "processing" the target shape. Processing the target shape could be decomposed in two steps: understanding the shape and defining an execution plan to create its features in the digital model. In our opinion, there was no evidence that participants who used the TUI were facilitated in understanding the target shape compared to those using the graphical interface, since the

pretest scores were similar and the populations were equivalent in terms of demographic data. Hence, **the benefits of the tangible setup could be found in an easier translation of the users' execution plan into interface actions**. The appearance of both the block and the other tangible tools provided affordances that made the recognition of related functions more immediate (Hornecker and Buur (2006)'s *Isomorph effects*) which would provide another explanation for the shorter time before the first cut in tangible condition. Similarly, the fact that the block represented a bounding box of its digital counterpart, allowed the participants to mimic the effect of cutting with their hands, for example masking part of it to have a better feeling of the final outcome. This "specificity" is absent in the graphical user interface, which is a composition of instances of general purpose elements, such as buttons or sliders. In addition, the mapping tool-function may have been facilitated by the unconstrained collocation of the tangibles in the workspace, which allowed participants to create their own "layout" for the tools, for example placing the cutter on the right or the wheel in the top left corners.

Q$_{Token}$ When the physical-virtual correspondence changes during the task, does a tangible interface become just a control "token"?

In spite of the fact that the literal correspondence became partial after each cut, the eye-gaze data showed the distribution of dwells toward the block throughout the whole experiment. This indicated that participants kept on looking at the control block and, consequently, the hypothesis that the tangible block becomes a "token" was not confirmed. Surprisingly, we observed that TUI participants actively acted in order to preserve the reference between the physical block and its virtual representation on the screen. The significantly higher average number of fragments created when using TUIs suggested an adaptation of the users to overcome the limitation of the interface. In fact, given that the average number of cuts did not differ in both conditions, the difference resulted from the TUI participants' tendency to keep most of the fragments till the end and to delete the unnecessary ones afterwards. Differently from the operational mode exhibited by GUI participants, this strategy clearly prevented the loss of digital-physical coupling. What were the properties that the participants were preserving? For instance, how did it matter in our implementation? The one-to-one mapping between the dimensions of the control block and its digital counterparts? The answer to these questions would require a more exhaustive study in which the independent variable could be related to geometrical properties or to the spatial relationship of the tangibles. However, this study pointed out that the extent to which a physical entity is in a state of literal correspondence with its digital representation could be defined by the mapping of the properties as well as by the temporal evolution of this same mapping. Furthermore, we saw that relaxing the correspondence over time had an impact on users' behaviour which could be or not be desirable according to the application domain.

This study was not exempt from limitations. Although the experimental task was designed for vocational apprentices, we could not conduct the study in an authentic setup but in a laboratory setting, recruiting undergraduate students. Participants were representative of a population having high spatial abilities and acquainted with both the use of CAD applications and 3D computer graphics. On one hand this factor limited the novelty effect due to the use of a new technology. However, to some extent, the highly skilled population might have prevented us from finding some additional effects and more solid conclusions about how tangibles scaffold spatial thinking.

4.5 Conclusions

To sum up, this chapter compared the effects of TUIs and GUIs on spatial reasoning from the eye-tracking perspective. Some of the typical cognitive advantages of tangibles that are usually reported in the TUI literature found support from the quantitative data of the participants' gaze behaviours. The difference in the gaze properties on some areas of interest provided us with clear indications on where and when the facilitation happened.

The successful application of the eye-tracking methodology encouraged its adoption as research tool to study the cognitive effects of tangibles or, more broadly, of physical entities when they are digitally represented in any mixed-reality system. This study provided us the premise to collect gaze data in the following two studies too.

5 Study II: Gaining an Intuition of Statics from Physical Manipulation

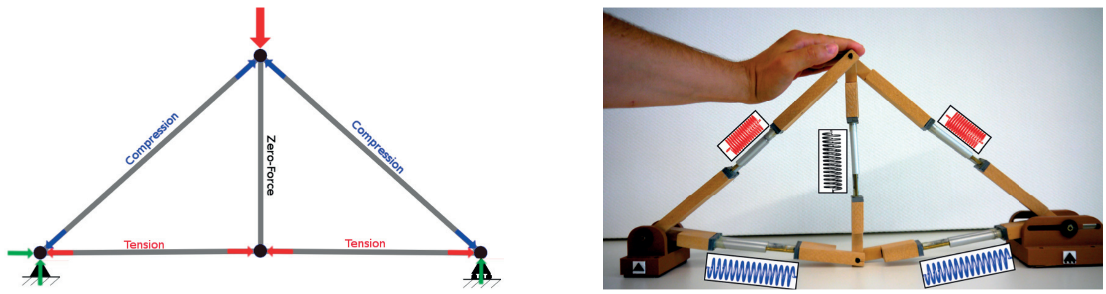
5.1 Introduction

At the time our interest was drawn by bringing statics in the vocational classrooms, the meetings we had with the carpentry teachers helped us in outlining the type of features an AR system should have for such a purpose. It seemed natural to begin with the analysis of truss structures, since these are one of the most common structures present in carpentry practice. As described in the chapter 3, a truss is a structure composed by straight elements joined together at their extremities. Analysing a truss consists in identifying the axial forces acting in the members for a given loading condition: if the force tends to shorten the member it is a compressive force. A force that tends to elongate the member is called a tensile force. Additionally, there could be some members which support no load, the so-called zero-force members. These are often used to increase the stability of the truss.

Employing physical models and augmented reality through tablets and smart-phones looked promising to us and to the teachers. The implementation of hands-on activities to explore statics and structural behavior is generally considered to be a fruitful practice. It is widely adopted by instructors since it allows them to create explicit connections between the subjects being taught and the applications in real-life scenarios.

The types of physical materials adopted in statics courses could be roughly categorized on a spectrum that goes from rigid to interactive models. Rigid models are small-scale representations of structures made of softwood, aluminium or other materials and typically used to test the effects of external loads, such as deformation or bending (Yazici and Seçkin, 2014; Solís et al., 2012; Romero and Museros, 2002b). Given the rigidity of the materials, usually those effects are quite imperceptible unless the limits of the materials' strength are exceeded which might damage the model. Interactive models try to overcome these limitations by embedding components into the models in order to magnify the phenomena. For instance, in case of truss analysis, the representation of axial forces could be done qualitatively by integrating springs in the truss beams, as in the solutions proposed by (Bigoni et al., 2012; Oliveira, 2008); alternatively, electronic sensors could be used to measure the forces (Dodge et al., 2011). Compared to rigid models, the interactive ones offer a higher degree of manipulation, thus they are more suitable to engage students in exploratory activities. Moreover, the feedback offered by these models (e.g. tangible, visual, haptic) could positively contribute to the outcome of the learning activities ((Zacharia and Olympiou, 2011) reviewed works and theories that could account for such benefits).

Inspired by the works on interactive models, we built a first prototype of small-scale wooden model which behaved as a simple truss (Figure 5.1). The prototype featured a spring mechanism at the centre of each beam, which was composed by four metal pipes that could slide on each other allowing a displacement of 2 cm in both directions (Figure 5.2). The members of the model were connected together by a nylon spacer passing through the extremities so that the connections could behave as hinged joints (Figure 5.3). The application of external forces on the joints by hands or by weights caused the mechanisms to either compress or elongate. Inside the pipes two springs guaranteed that the mechanisms were returning to the rest position when no force was applied. A wooden strip could be used to lock a single mechanism and to make the related beam rigid (Figure 5.4).

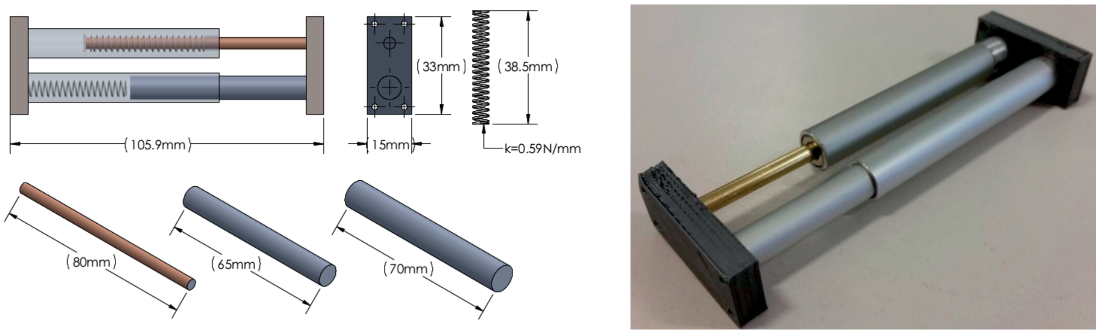


(a) (b)

Figure 5.1 – Prototype of a physical model to explore statics.

The physical model alone described the behavior of the structure qualitatively well, it could be directly manipulated and it provided tangible feedback. As a matter of fact, after we built the first prototype the role of the augmentation appeared unclear. Hence, in order to shape the virtual content for the augmentation, we needed to investigate the potential of the prototype as a learning tool and its possible limitations.

The study presented in this chapter aimed at assessing the effectiveness of the aforementioned prototype for fostering static reasoning skills in carpentry apprentices. More specifically, we wanted to evaluate the impact of the manipulation and of the consequent feedback from the prototypes on the apprentices' ability to identify the forces acting in truss structures. The study was framed as a comparison between receiving the feedback from the manipulation of the prototype and receiving it from an instructor. Since in both conditions participants worked with the physical models of the structures, the critical point of the study was whether discovering through manipulation might improve the understanding of the concepts underlying the learning task. This also meant that learners got more control on the pedagogical activity. As for



(a) (b)

Figure 5.2 – Details of the spring mechanism.

Figure 5.3 – A hinged joint.

Figure 5.4 – Wooden strip to lock the spring mechanism.

Tangible User Interfaces (TUIs), the utility of manipulating concrete materials is controversial and the effects on the learning gains are inconstant (Han et al., 2009; Zacharia and Olympiou, 2011; Alfieri et al., 2011; Carbonneau and Marley, 2012). Thus, the study contributed to the discussion about the relation between physical manipulation and learning. The design of the experiment included pre-test, intervention and post-test. The hypotheses underlying the comparison were two.

$\mathbf{H}_{Outcomes}$ The interaction with our prototype and the hands-on exploration of the physical model would lead to higher learning outcomes than the ones achievable in absence of the feedback from the springs.

This hypothesis has been investigated by comparing participant's performances in each of the pre- and post-tests and during the intervention phase in which we employed the think-aloud protocol to gather data on the modalities used by participants to carry out solutions for the proposed exercises.

$\mathbf{H}_{Visual\ Exploration}$ When using our prototype, the participants' gaze would be more focused on the areas of the structures that are relevant to the resolution of the exercises.

In addition to the think-aloud protocol, we also gathered gaze data through an eye-tracking device. In order to create a baseline for the comparison of the apprentices' visual search patterns, we collected eye-tracking data from experts who solved the same exercises apprentices went through. According to the *information-reduction hypothesis* of Haider and Frensch (Haider and Frensch, 1999), expertise is based on a "reduction in the amount of information that is processed. [The hypothesis] holds that participants learn, with practice, to distinguish between task-relevant and task-redundant information and to limit their processing to task-relevant information". The finding from the meta-analysis of Gegenfurtner and colleagues (Gegenfurtner et al., 2011) tended to confirm these assumptions since, when comparing the gaze behavior of experts and non-experts, the former exhibits more fixations on task-relevant and fewer fixations on task-redundant information. This reflects the selective attention of experts, thereby, experts' data was used as reference to identify task-relevant areas and to investigate different scanning approaches among the participants. Think-aloud data was gathered from experts too, however its main purpose was to outline the way experts approach structural analysis qualitatively and consequently to inform the design of the augmentation.

5.2 Experimental Setup

5.2.1 Qualitative Truss Analysis: the Tension-Compression Task

As said in chapter 3, roof trusses are structures that apprentices generally encounter at the construction sites, thus developing a comprehension of the forces acting in them is part of the school curricula. The experimental task for the following study consisted in a series of exercises, each of which required the participants to tell the type of axial force acting in a truss beams subjected to one or two forces. The axial forces could be of three types: tension, compression and zero-forces. Other non-axial forces were negligible. The exercise should be solved only by visual inspection, without using paper and pen, leveraging the intuitive understanding of the problem to find the solution to static equilibrium.

5.2.2 Experimental Conditions and Materials

Three experimental conditions were defined: *tangible*, *verbal* and *expert*.
Carpentry apprentices were assigned to the two conditions *tangible* and *verbal*. The difference between the two conditions lay (1) in the way subjects received feedback on their responses to each exercise of the experimental task; (2) in the freedom of exploration given in order to reflect on the feedback. In the tangible group, the participants could check their solutions by directly looking at the spring mechanisms while applying forces with their own hands. In the verbal condition, the feedback was provided by the experimenters who indicated the correct responses. In both conditions feedback was given at the end of the exercise but

the experimenters did not provide any explanation of why the answers were correct/wrong. Furthermore, before moving to the next exercise of the series, extra time was given to the participants in order to let them elaborate the feedback. During this additional time, the participants in the tangible condition had the chance to test their hypotheses on the structure behavior by manipulating the models and applying any external force of their choice. Since no time limit was set, apprentices could explore other configurations than the one proposed in the exercise. For instance, they could check what happens when forces are applied on different joints. We hypothesised that the participants would profit from this discovery phase because their reasoning could be integrated with multiple hands-on tests. This would allow them to produce several loops of hypotheses generation and evaluations which which in turn would lead to the intuition of the physics principles behind the exercises. In the verbal condition, the discovery aspect was absent, hence the reflection on the feedback could be built only upon the information collected from the experimenters and from the previous exercises of the series.
An important aspect of our experimental design was that the materials used during the intervention were the same in both conditions. Assuming that, to some extent, the analogy between a timber beam and a spring could be effective to illustrate a hidden phenomenon (compression or tension of the wooden fibres) and to understand it, such analogy was explicit both in the tangible and in the verbal condition.
The *expert* condition included graduate students with a strong background in statics. Experts solved the same series of exercises used for apprentices and received the feedback as participants in tangible condition.

For the pre- and post-test evaluation, the assessment of the participants' knowledge about statics required the development of a paper-based test. Although several assessment tools are available for testing mechanics and statics knowledge (Savinainen and Scott, 2002; Steif and Dantzler, 2005), these tests are generally directed at high-school students or undergraduates. According to the carpentry teacher who helped us in designing the experiment, the topics covered in the test were too advanced for carpentry students and the questions needed to be framed in the carpentry context. As a consequence, we co-designed with the teacher a test focused on the analysis of truss structures which included seven questions. Each question consisted in identifying the nature of the axial forces in three beams, choosing between compression, tension and zero-force (Figure 5.5). Among the 21 correct answers, 7 were assigned to each force type. The maximum score for the test was 21 points, since one point was given for each beam correctly determined in the seven questions. The difficulty of each question was ranked by two EPFL professors of structural engineering. Finally, we conducted a pilot study with 29 carpentry apprentices in a vocational school in Germany in order to validate the test and its suitability for carpentry students. From the result we established that the optimal time limit for the test was of 9 minutes.

The intervention phase consisted in a series of exercises involving the analysis of eight models of roof structures, seven of which were two-dimensional and one was three-dimensional (Figure 5.6). As for the previous test, the structures and their order in the series were chosen in collaboration with the carpentry teacher. The first four models and the last one can be

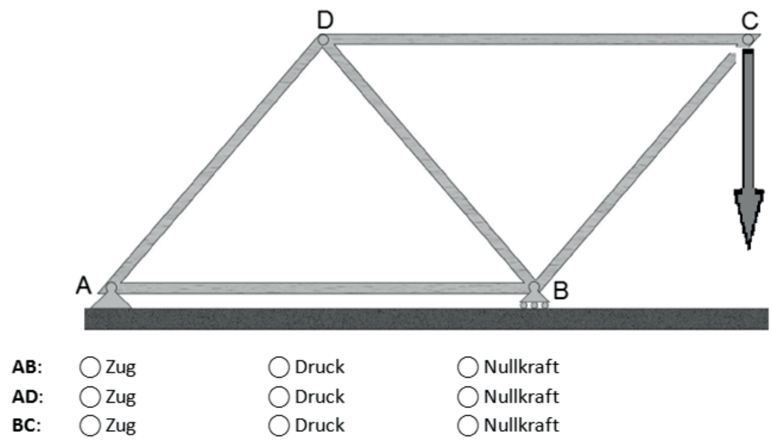
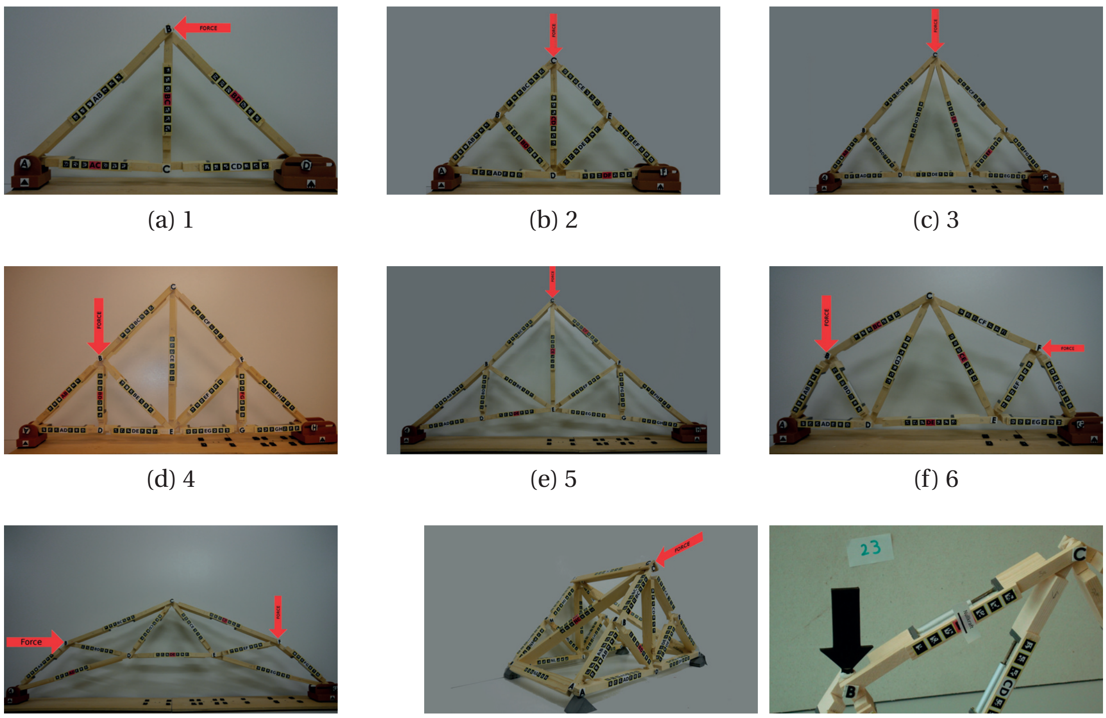


Figure 5.5 – Example of question item from the statics knowledge test.

considered as a continuum since they are variations of common triangular-shaped roofs featuring flat bottom chord. Thus, the forces in some beams were the same across the models. The fifth model, although similar to the previous ones, posed a challenge because the bottom chord was not straight. Lastly, in exercises 6 and 7 the models were resembling less popular trusses and two forces with different magnitudes were applied on them.



(a) 1 (b) 2 (c) 3

(d) 4 (e) 5 (f) 6

(g) 7 (h) 8 (i) The arrow used to show the external forces.

Figure 5.6 – The eight trials used in the experiment.

In all the two-dimensional models, the extreme bottom left joint was designed as pinned, which provided restraints on translations, whereas the right one was roller which provided only vertical reaction and allowed the joint to slide sideways.

Regarding the one three-dimensional structure present in the experiment, it was not possible to craft the joints as pinned, hence the physical model could not provide any feedback. The supports were located at the four extreme bottom joints, two of which were pinned and the other two were rollers.
During the exercises, the external forces acting on the joints were represented by black 3D-printed arrows (Figure 5.6i). For trials 6 and 7 two sizes were available for the two forces of different magnitudes that were applied on the structures.
The fiducial markers glued on the structures had the only purpose of defining some visual features used to process data from the eye-tracker.

5.2.3 Participants and Procedure

For the expert condition, we recruited EPFL master degree students or doctoral candidates in civil engineering. The inclusion criterion was a final grade of 5 or higher in the course(s) on statics. The expert condition involved N = 6 participants (1 female) with an average age of M = 24.33 (SD = 2.50). Two of the participants were doctoral candidates; four of them finished their Bachelor and were currently doing their Masters. None of them had professional experience. For the experts, the experiment was conducted in English since all of them spoke English fluently.
The carpenter apprentices were recruited from the *Berufsbildungszentrum Bau und Gewerbe* vocational school in Luzern. In total, the experiment involved 24 apprentices, all males, who were randomly assigned to one of two experimental conditions. Five of the participants were in the first year of training, nineteen in their second year. The experiments with apprentices was conducted in German. Table 5.1 offers a detailed characterization of demographic data of the two apprentices' groups. One-way ANOVA showed that there was no significant difference between these two groups regarding their age and their self-reported prior knowledge.

The experiment included four parts: (1) two paper-based tests, namely the Mental Rotation Test and the test for assessing participant's knowledge of statics; (2) the intervention, (3) the post-test which was the same test used in the first part; (4) the follow-up interview. Experts were not asked to complete the post-test.
In the first stage, the Mental Rotation Test (MRT) was the same used for the previous study, consisting in twelve questions having two correct answers each. The time limit was of nine minutes. The pretest about the statics knowledge began with a introductory page explaining the task and the questions. The experimenters were ready to guide the participants and to clarify participants' doubts. The time for the pretest was limited to nine minutes.

After completing the paper-based tests, participants were asked to wear an eye-tracking device and were introduced to the intervention stage and to the think-aloud method. Before starting

Table 5.1 – Apprentices' demographic data.

	Apprentices (n=24)	Tangible (n=12)	Verbal (n=12)	Significance
Age	17.25 (SD:1.58)	17.83 (SD:1.99)	16.67 (SD:0.65)	F(1,22)=3.72, p=0.067
Familiarity: Static concepts (from 1 to 5)	2.92 (SD:0.88)	3.00 (SD:0.74)	2.83 (SD:1.03)	F(1,22)=0.21, p=0.653
Familiarity: Acting forces on a truss construction (from 1 to 5)	2.96 (SD:0.75)	2.83 (SD:0.84)	3.08 (SD:0.67)	F(1,22)=0.66, p=0.427
Experience: Bridge Building Game or any statics simulation software (from 1 to 5)	1.50 (SD:0.72)	1.50 (SD:0.67)	1.50 (SD:0.80)	F(1,22)=0.00, p=1.0

each exercise, a wooden model was placed in front of the participant (Figure 5.7). The spring mechanisms were locked, thus manipulating the structure was not providing any feedback. The exercise began right after the 3D-printed arrows depicting the external forces were placed on the joints of the model. For each model, the participants were asked to determine whether three beams were under tension, compression, or zero-force members. The beams were marked in red and the participants gave their solutions by sticking printed labels on them. The labels could also be used to mark down the forces acting in any other beam.

Every time participants completed one exercise, they received the feedback about the correctness of their answers. In both the tangible condition and the experts one, the experimenters only stated if the answers were correct or wrong. The actual solutions were provided through the spring mechanisms. The participants could remove one locking strip at a time and could directly apply the forces with their hands to see how the chosen beam reacted. They could test as many beams as they felt necessary.

Differently, the participants in the verbal condition were not allowed to unlock any spring, but they received verbal feedback provided by the experimenter ("right" or "wrong") and the correct answer in case they were wrong.

To make the processing of the feedback explicit, before receiving the feedback the participants were asked to give an explanation and to verbalize the reasoning that brought to the wrong answers. Similarly, after the feedback the experimenters asked the participants to provide an alternative explanation that could justify the correct solutions.

Regarding the think-aloud protocol, in the case of apprentices it was employed only in item 2 and item 7 in order to reduce cognitive load. The experts were asked to think aloud while solving the whole series. During the think-aloud session, the participants had to verbalize their reasoning when analysing the structures. The experimenters prompted the participants to keep thinking aloud if they paused for too long and took notes about points that needed clarification. These open points were straightened out during the follow-up interview.

After completing the intervention stage, the apprentices completed the post-test, which was identical to the pre-test. The experiment ended with a semi-structured interview which revolved mostly around the participants' approaches to determine the forces acting on the beams. The open questions noted by the experimenters during the intervention were clarified and the participants were also asked if the feedback they received (tangible or verbal) was helpful to understand the acting forces and to improve the performance. Furthermore, the feedback about the prototype and its usability were gathered, as well as what the participants thought to be the role of statics in their working daily practice. The whole experiment took approximately 1 hours and 10 minutes for the apprentices, versus 45 minutes for the experts.

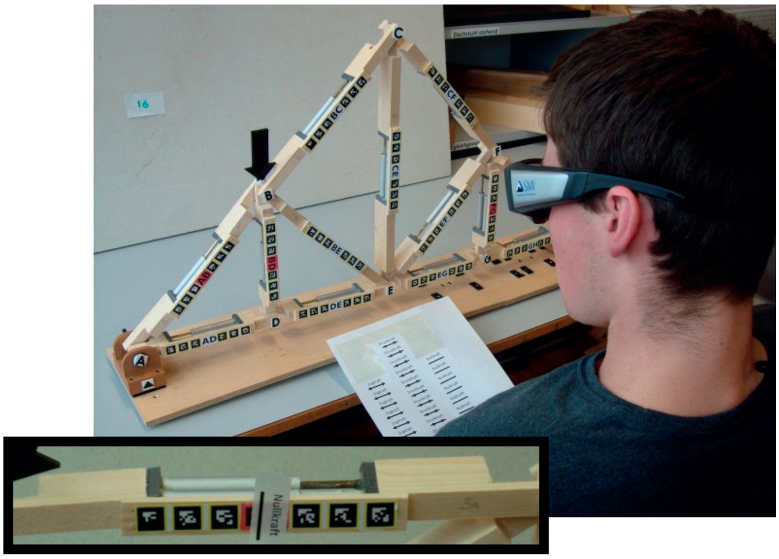


Figure 5.7 – The setup of the experiment.

5.3 Statistical Analysis and Findings

The software employed for the statistical analysis were R v3.1 (R2014) and IBM SPSS Statistics 2013.

Apprentices' Performances In the pre- and post-test, the participants received one point for each beam correctly determined, hence the maximum score was 21. The score in the intervention phase was computed in the same way and the maximum score was 24. The scores shown in Figure 5.8 have been normalized between 0 and 3 in order to make comparisons between pre-test, intervention and post-test.

The effect of the phase (pre-test, intervention or post-test) was statistically significant, due to the average score in the intervention phase being lower than the scores in the pre and post

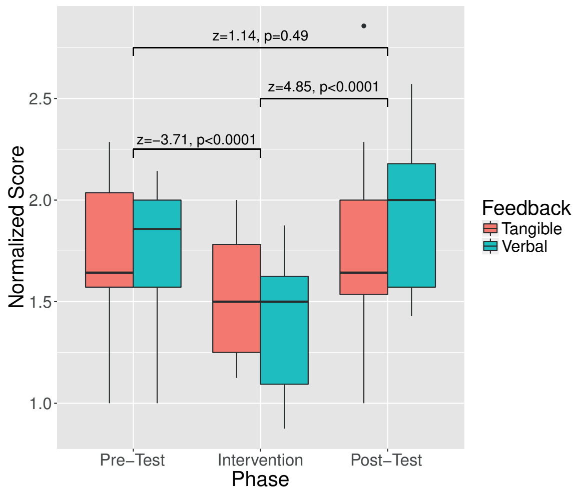


Figure 5.8 – Participants' scores in pre-test, intervention and post-test.

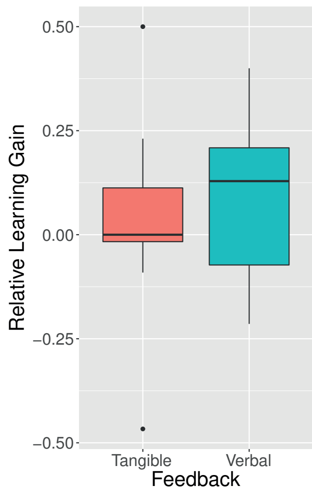


Figure 5.9 – Relative Learning Gain.

test (mixed-model $\chi^2(2) = 21.336$, p<0.0001). This difference will be investigated further when analysing the participants' mistakes. The pre-test and post-test scores were not significantly different and neither an effect of the feedback condition nor an interaction effect between phase and feedback were observed.

The Relative Learning Gain (RLG) shown in Figure 5.9 was computed using the following formula:

$$RLG = \begin{cases} \frac{score_{post-test} - score_{pre-test}}{21 - score_{pre-test}} & \text{if } score_{post-test} - score_{pre-test} \geq 0 \\ \frac{score_{post-test} - score_{pre-test}}{score_{pre-test}} & \text{if } score_{post-test} - score_{pre-test} < 0 \end{cases}$$

The RLG was on average very marginal (6%, SD: 21). The apprentices who received the verbal feedback had an average RLG of 10%, whereas those who received the feedback from the spring mechanisms gained on average 4%, but this difference was not significant (Welch's F[1, 21.7]=0.40, p=0.53).

The Mental Rotation Test score was computed by assigning one point when the participant marked both the correct answers of each question, hence the maximum score was 12 points. The scores in the two experimental groups, tangible and verbal, were found to be homogeneous and apprentices obtained on average 7.8 points (SD: 2.57, F[1,22]=1.44, p=0.24). We found a significant medium correlation between the MRT score with the pre-test score (r=0.38, p=0.040) and with the post-test score (r=0.50, p=0.014). However, there was no significant correlation with the performance during the intervention (r=0.07, p=0.712). Thus, the test on paper seemed to disadvantage apprentices having low spatial skills.

The relationship between self-reported prior knowledge of the novices and the performance shown during the experiment was examined using Spearman's correlation. There was a significant medium correlation between the score of the question "how often do you play Bridge Building game or use a statics simulation software?" and the pretest (r_s=0.55, p=0.005), the intervention (r_s=0.44, p=0.03) and the post-test (r_s=0.42, p=0.04). There was also a significant medium correlation between familiarity with acting forces on a truss construction ("how familiar are you with acting forces on a truss construction") and the post-test score (r_s=0.45, p=0.03), probably because the intervention phase helped students to "refresh" their prior knowledge. There was no significant relation between years of training and performance in all parts of the experiment, however from the final interviews it seemed that the type of occupation played an important role. When looking at the lowest and highest scores in the post-test, the former was achieved by an apprentice who worked in a company manufacturing doors, hence he has been barely exposed to scenarios in which statics becomes relevant. On the other hand, the highest score (20 out of 21) was from an apprentice working on the construction site of ski jumping ramps. The apprentice explained that, although concepts related to statics are not explicit on the workplace, he gained some intuitive understanding from his practice. His understanding of structural behavior was grounded on a blend of experiences acquired at the workplace. For example, technical terms like *collar tie*, which is a horizontal beam present in many trusses, recalls the idea of a tension member. Similarly, the instructions to setup the scaffolding or the choice of specific fasteners on some joints implicitly communicate the stresses acting in a structure and contribute to build a comprehension of their behaviors.

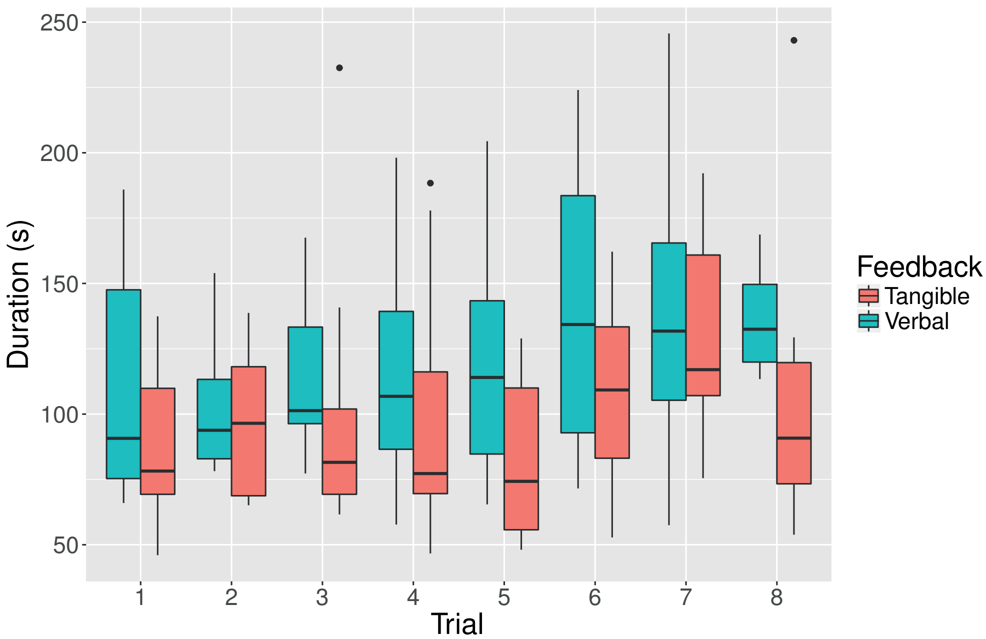
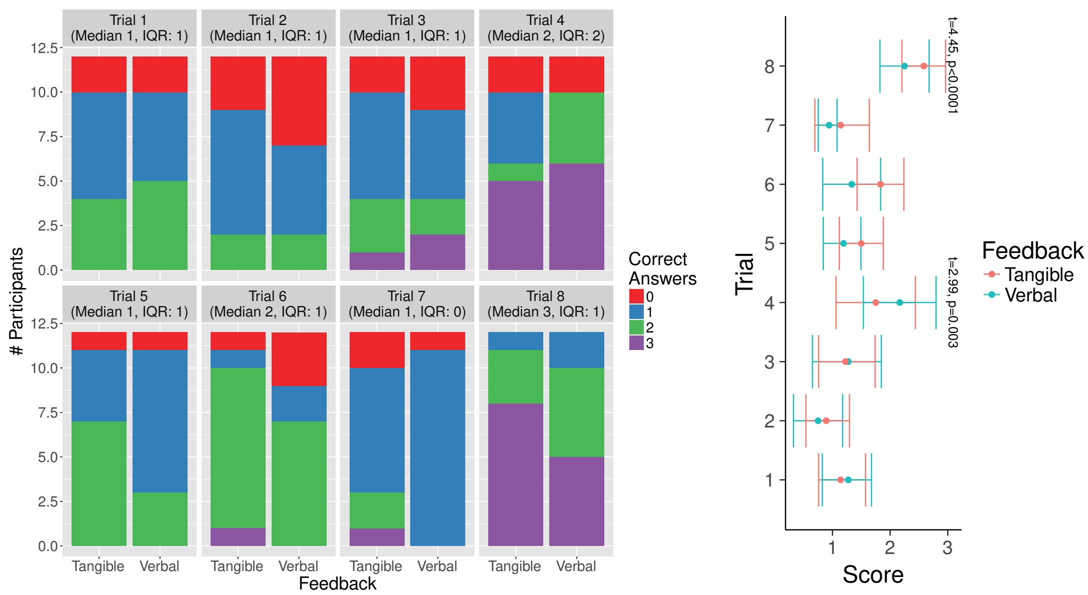


Figure 5.10 – Task duration for each trial.

The duration of the intervention in total took slightly less in tangible condition (35 min, SD = 4 min) than in verbal one (38 min, SD = 7.5 min). From Figure 5.10 we can see that the duration of the reasoning phase[1] was longer in the verbal condition, especially after trial 2. We investigated the difference building a mixed-effects model, which showed a significant increment of duration in the verbal condition (134s, SE:6) compared to the baseline associated to the tangible group (101s, SE: 6, $\chi^2(1) = 17.07$, p<0.0001).

Figure 5.11a shows the number of participants who identify correctly none, 1, 2 or all the forces in each trials of the intervention phase. In terms of numbers of correct answers, we could observe neither a main effect of the kind of feedback received during the intervention (mixed-effects model, $\chi^2(1) = 0.605$, p=0.43) nor an interaction effect between feedback and trial (GLM, $\chi^2(8) = 2.8574$, p=0.64). Overall, the median scores achieved on trial 4 and 8 were significantly higher than the ones reached in the other trials (GLM, $\chi^2(7) = 29.449$, p<0.0001). The results would suggest that there was no monotonic increment during the intervention phase. Nevertheless, as previously said, the first 4 exercises and the last one involved structures belonging to the same class of trusses. Hence, by excluding the trial 5,6 and 7, the result could be read as a significant increment of the scores when dealing with that specific type of trusses.



(a) Distribution of the scores

(b) Average scores with 95% CI

Figure 5.11 – Apprentices' scores in the intervention phase.

During the time dedicated to the exploration, the apprentices in the tangible condition unlocked 16 springs as median value (IQR: 3). Most of the springs were unlocked during trials 1 and 2 (median: 3, interquartile range: 2), whereas in model 4 the median value was only 1 (interquartile range: 2). We did not find any significant correlation between unlocked springs and both the intervention score ($r_s = 0.34$, p=0.28) and post-test score ($r_s = 0.36$, p=0.24). In both conditions, the duration of the exploration phase was not significantly correlated with the intervention score or the post-test score.

[1] The phase between the beginning of the trial and the feedback.

Table 5.2 – The annotations used for the analysis of participants' explanations.

Annotation	Description	Example
Gesture	The participant was gesturing.	Representing the path of the forces with fingers
Explanation	The participant gave an explanation for the analysis.	"Because the force is coming from there..."
Consequence	The participant drew a consequence of what was explained or observed.	"... this part will be shortened"
Identification	The participant stated the nature of the force acting in a beam.	"...thus, the beam is under compression."
Negation	The participant rejected a previous expression.	"Ah no, I was wrong."
Analogy	The participant expressed similarities with previous models or beams.	"For this beam it's basically like before"
Repetition	The participant repeated previous expressions.	
Meta-cognition	The participant's expressions showed meta-cognition.	"I have a situation in this node, I cannot understand it really well. Maybe I made a mistake here."

Verbalization of Apprentices' Reasoning The participants were asked to provide an explanation before and after receiving each feedback and to verbalize their reasoning in the think-aloud trials 2 and 7. The audio and video streams have been transcribed using the software ELAN and annotated according to the coding scheme shown in Table 5.2. The quality of the explanations was ranked by three independent raters on a scale from 0 to 5. The criteria for good quality included, for example, that participants took into account the different supports of the structures and the reactions to the external forces. Hence, the participants could reach a high quality score even if they gave a wrong answer. Among the raters, one was a carpentry teacher of statics on a vocational school. The inter-rater reliability was found to be Krippendorff's α=0.72, which could be considered adequate.

The only difference emerging from the quantitative analysis of the dialogue codes was that the proportion of the "identification" code was higher for apprentices receiving the verbal feedback compared to the other group. Apprentices in the verbal condition tended to state explicitly what were the forces acting in the beams (average ratio: 0.26, SD: 0.09), whereas this was less common for apprentices in the tangible condition (average ratio: 0.17, SD: 0.10, Welch's t-test t(21.72)=-2.40, p= 0.025). These results will be discussed in the light of the differences found between the approaches of the two groups to visual exploration.
Lastly, the analysis showed a significant negative correlation between explanation and intervention score (r=-0.55, p=0.005) and a positive correlation between analogy and intervention

score (r=0.36, p=0.049).

In general, the apprentices found difficulties in verbalizing their reasoning and in providing exhaustive explanations. The reasoning was typically narrowed to the analysis of isolated portions of the structures, usually subdivided into triangles, which the apprentices knew to be stable geometries. The quality of the explanation in 54 out 74 cases, in which explanations both before and after the feedback were available, increased after receiving the feedback. However, the quality decreased in 13 cases. We could not observe any noteworthy variation between the two experimental groups.

Mistakes In order to get a finer description of what kind of mistakes were made, we considered the ratio of correct answers given for each of the three types of forces, namely tension, compression and zero-force. Since there was no significant variation between the experimental conditions, we conducted the analysis aggregating the data from both apprentices' groups. Figure 5.12 shows the ratio of correctly identified elements in the experiment phases. The type of force and the experiment phase were both found to have a significant effect on the ratio of correct answers ($F[2,207]= 15.97$, $p<0.0001$; $F[2,207]= 10.00$, $p<0.0001$). Additionally, there was a significant interaction between the two variables ($F[4,207]= 4.68$, $p=0.001$). The results of the post-hoc Tukey analysis could be summarized as:

- The drop in performance seen in the intervention phase compared to pre- and post-test was mostly due to a significant lower ratio of correct answers for the compression force ($p<0.0001$ in both pairwise comparison);
- In the pre-test the ratios of the compression and tension forces were significantly higher than the ratio of the zero-forces (both $p<0.0001$), whereas in the post-test the only significant gap was between compression forces and zero-forces ($p=0.01$). Thus, in the post-test the participants' performance on zero-forces got closer to the ones of tension forces. However, no significant difference emerged between pre- and post-test ($p=0.051$).
- In the intervention phase, the participants detected more correctly tension forces than both compression forces ($p=0.4$) and zero-forces ($p=0.4$).

When we analysed the confusion matrix of the given and correct answers, we could not see any significant tendency of the participants towards specific answers. For instance, when the correct answer was "tension", the occurrence of "compression" as wrong answer was similar to the one of "zero-force".
Among the difficulties posed by the task, a particular effort was required to keep track of the forces identified in a structure and to propagate them in order to determine the remaining ones. Thus, it was not surprising that a source of mistake in determining the force of a beam

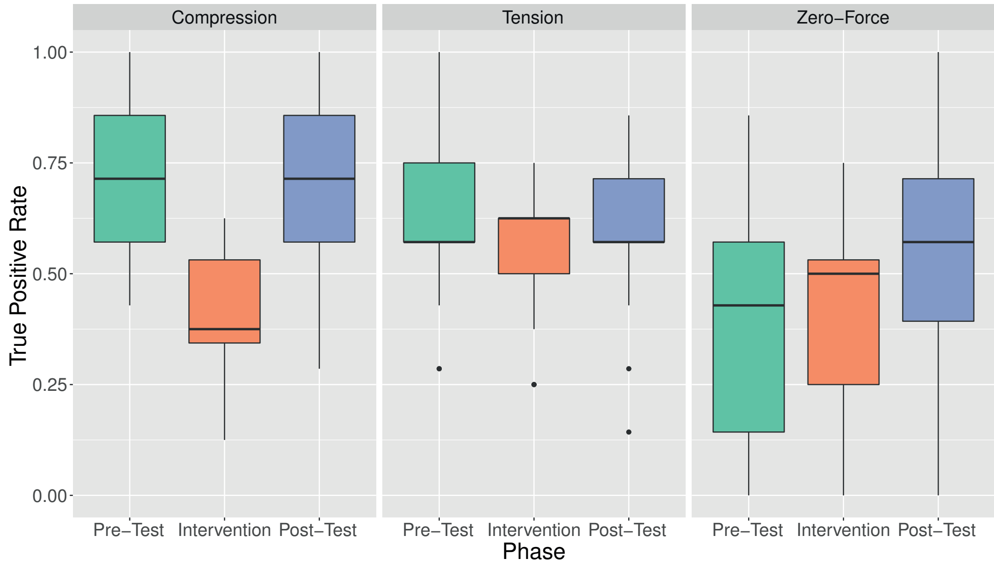


Figure 5.12 – Ratio of correct answers for each phase and force type.

arose from the distance[2] between the beam and the applied force. The analysis confirmed that apprentices were sensitive to this difficulty, since the odds of correctly identify the axial force of beams at distance 3 decreased significantly by a factor -0.75 compared to both cases when the distance was 1 or 2 (SE: 0.11, GLM, $\chi^2(2) = 6.08$, p=0.047).

Comparison with Experts' Data The reader can find the terminology used for the eye-tracking in subsection 2.3.2. The fixations were labelled according to the element of the structures that they hit (e.g joint A, beam AB and so on). Due to technical issues, the gaze data gathered during the last trial could not be analysed.

As it was expected from participants in the expert group, their scores in both the pre-test and the intervention phase were significantly higher than the apprentices' scores: the pre-test average score was 2.17 (SD: 0.28, $t(28) = 2.929$, $p = 0.007$) while in the intervention it was 2.23(SD: 0.50, $t(28) = 4.667$, $p < .001$). The spatial skills of experts did not differ significantly from the one of the apprentices, since their average MRT score was 7.00 (SD: 2.37, $t(28)= 0.682$, $p =0.50$).

Regarding the distribution of the fixations on the structures, we started looking at the amount of time spent looking at either the joints or the beams of the structures. Figure 5.13 shows the time the participants were fixating the joints of the structure over the total fixation time. Experts allocated on average 45% of their fixation time at the joints, whereas apprentices in the verbal condition 40% and those in the tangible condition only 32%. The main effect of the condition was found to be significant (GLM, $\chi^2(2) = 44.309$, p<0.0001). Also the pairwise

[2]The distance was defined by the number of joints present on the path between the beam and the force, which ranged from 1 to 3.

comparison between the three levels was always significant (static vs. expert p=0.034, tangible vs. expert and tangible vs. verbal p<0.0001).

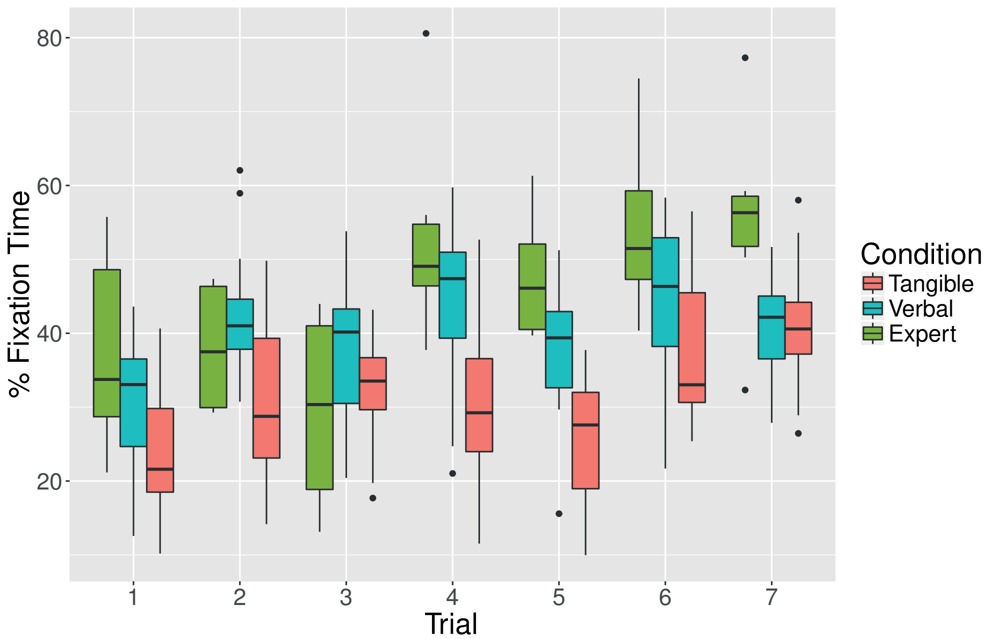


Figure 5.13 – Percentage of fixations on the joints.

In addition, we aggregated the experts' data and built the histograms of the fixations on each joint and beam for the first seven models of the intervention phase. The seven histograms represented the saliency for each element of the structures from which we computed how close the distribution of apprentices' gazes matched those of the experts. The measure used to estimate the overall dissimilarity was the Kullback-Leibler divergence (Le Meur and Baccino, 2013)

$$KL(H_i^j, H_E) = \sum_{k \in areas(j)} H_E(k) log\left(\frac{H_E(k)}{H_i^j(k)}\right)$$

where $H_i^j(a)$ is the proportions of fixations on element a of structure j for apprentice i. Similarly, H_E denotes the empirical distribution for the experts. The measure tends to zero as the two distributions gets similar, but it does not have an upper-bound.

The KL divergence for each trial is shown in Figure 5.14. The apprentices who received the feedback from the springs mechanism began to diverge more after trial 2. The effect of the condition has been assessed via mixed-effects model, which estimated the difference between the two groups to be 1.43 (SE: 0.21 $\chi^2(1) = 6.28$, p=0.012).

The divergence appeared mostly on models 3, 4, 5, 6. The result could be better understood when looking at the saliency maps which were built from the fixation distributions. Two explicative examples came from the maps for models 4 and 5 which are presented in Figure

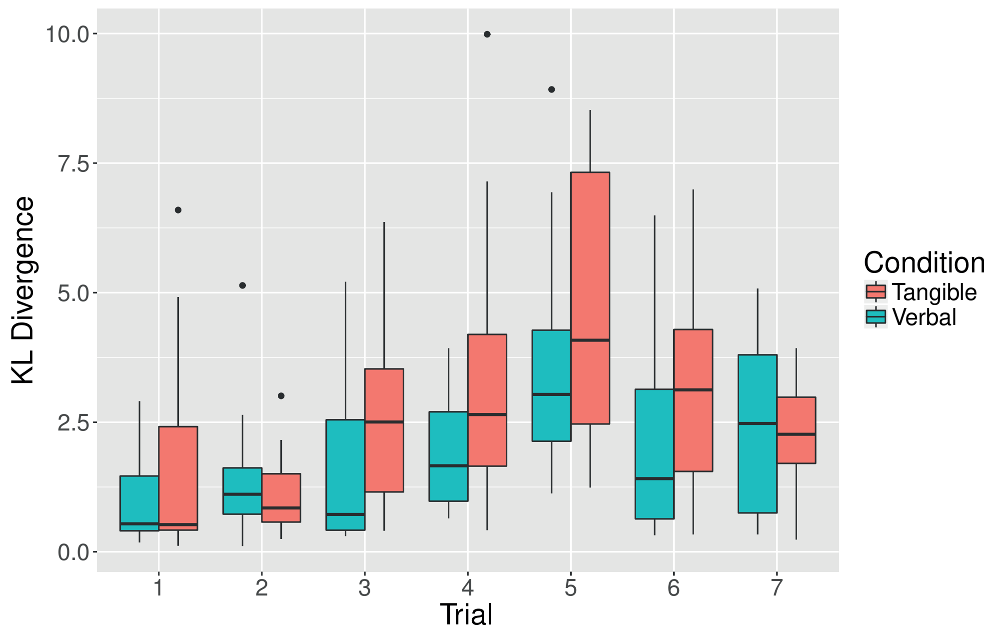
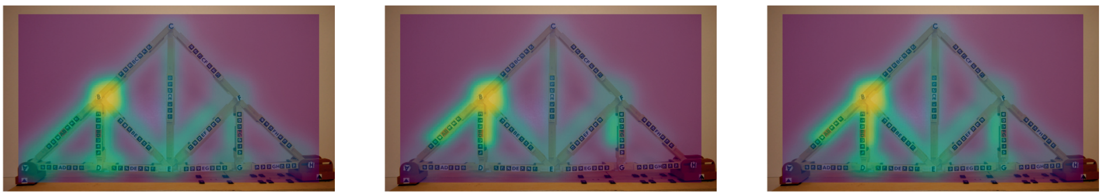
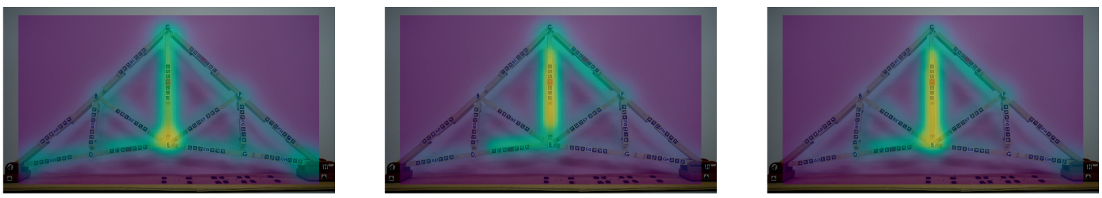


Figure 5.14 – Kullback-Leibler divergence of the apprentices' distribution of fixations compared to the experts' one.



(a) Experts. (b) Tangible Condition. (c) Verbal Condition.

Figure 5.15 – Saliency map for model 4.



(a) Experts. (b) Tangible Condition. (c) Verbal Condition.

Figure 5.16 – Saliency map for model 5.

5.15 and 5.16. In model 4, the gaze of the experts covered almost each joint of the structure and the map of apprentices in the verbal conditions looks very similar to it. On the contrary, the participants in the tangible group did not allocate much visual attention to the joints at the bottom. In model 5, as we previously said, the peculiarity was due to the beams at the bottom that were not straight. Thus, the configurations of the forces at the central joint was quite different compared to the previous structures. This criticality emerges clearly from the two maps 5.16a and 5.16c, but not from the apprentices' one in tangible condition, that seemed to not pay much attention to it.

However, in terms of scores achieved in the seven trials and the relative learning gain, we could not find any significant correlation neither with the percentage of fixation on the joints ($r = -0.05$, p=0.55) nor with the KL divergence from the experts' saliency maps ($r = -0.08$, p=0.27).

In contrary to the apprentices, the experts referred to the joints of the structures during their verbal explanations. Typically their analysis began with considerations about the reactions offered by the supports. Four of them explicitly stated the conditions for the equilibrium and three experts used their fingers to build the polygons of the forces at the joints to check their resultants. Their qualitative reasoning was largely influenced by the Cremona-Maxwell method, which is a graphical method for analysing trusses taught during the first years of university.

5.4 Discussion

The general picture offered by the analysis could be summarized in the absence of differences between the two apprentices' conditions in terms of learning outcomes, thus rejecting the $H_{Outcomes}$ hypothesis. At first glance both the average post-test score and the RLG were higher in the verbal condition compared to the tangible one, however the high variance resulted in a lack of statistical significance.
A noteworthy result was the positive correlation between MRT score and both pre- and post-test scores, and the absence of correlation with the intervention score. The positive relation between spatial abilities and problem solving in structural behavior has emerged already from the work of Alias, Gray and Black (Alias et al., 2003), as well as from works focused on other STEM subjects (Uttal and Cohen, 2012). The absence of correlation with the intervention score supported the claim that having a physical representation mitigates the difficulty of users with low spatial abilities, which is one assumption for using physical materials (including TUIs) as learning technology in STEM fields (Clifton et al., 2016).

In the intervention phase, the duration of the participants' reasoning before the feedback was given was 30s shorter in the tangible condition than in the verbal one. The difference was present since the beginning of the intervention phase, thus the result might be due to the fascination for the spring mechanisms and to the participants' desire to manipulate the tool. Similarly to the *manipulation temptation* concept reported by Do-Lenh et al. (Do-Lenh et al., 2012), the backlash of having a high freedom of manipulation and a playful learning experience was a decreasing attention towards the understanding of the problem. However, in our experiment the fascination did not seem to last long. Although the participants were encouraged by the experimenters to explore the behavior of the models, the number of springs unlocked after the feedback was given was generally low. It was not possible to say whether the participants' attitude to refrain from exploring was due to either the inhibition caused by the experimental setup (e.g. "I already unlocked a couple of springs, I should not overdo it.") or to a perceived uselessness of the tangible feedback. In either way, we did not see any relation between the number of springs unlocked and the learners' performance.

The number of correct answers showed an increasing trend for the first four models, then a drop and again an increment on the last structure. As mentioned in the analysis, although the structures were sorted by increasing difficulty, the first four structures and the three-dimensional one belonged to the same class of standard trusses having a triangular shape. When isolating these four models, there was indeed an increment of participants' scores, which could be attributed to the recognition of the common pattern in the four layouts and the transfer of this knowledge. The medium positive correlation between the dialogue code *analogy* and the intervention score gave additional support to this interpretation. However, when moving to structures having different layouts, finding analogies became more difficult, which led to a higher number of mistakes. As suggested by the findings of Chi, Feltovitch, and Glaser (Chi et al., 1981), apprentices might have tended to categorize the problem by the explicit features (e.g. layouts, direction of the force) rather than by the underling physics principles, which made difficult to reason by analogy when a new scenario was not highly similar to the previously encountered ones.
The quality of the explanations given right before and after the feedback generally improved, regardless of the experimental condition. The apprentices seemed to have developed a better understanding of the physics concepts, but this did not result in a significant improvement of the outcomes. Most likely, the experience gathered through the experiment did not provide enough data to build an effective "theory" to solve the problems and it only superficially scratched the body of participants' misconceptions. This interpretation could be linked to another result: the more participants used explanations during the intervention phase, the lower was their score in such phase. According to recent works on the *self-explanation effect* (Williams and Lombrozo, 2010; Legare et al., 2010), when learners strive to find regularities and to abstract rules, the search for explanations lead people to connecting small samples of unrepresentative observations, which results in inferring incorrect generalization and create an *illusion of discovery* (Rozenblit and Keil, 2002). Probably the design of our setup could not break these wrong beliefs. In the tangible condition, the participants were supposed to have an advantage, thank to the fact they could have dissipated their doubts by means of the feedback from the models. However, this was not the case. A better design could, for instance, involve the collaboration between participants, who would benefit from a mutual explanation and from providing sensible justifications to their answers(Jermann and Dillenbourg, 2003).

Regarding the mistakes, the apprentices found particularly difficult to grasp the concept of zero-force. Recalling the results, the amount of correctly determined beams in the pre-test was significantly lower for zero-force members compared to compression and tension ones. However, in the post-test the difference is significant only with compression forces, which could be read as an improvement. A common question during the experiment was "If it doesn't carry any load, can't we just remove it?". Zero-force members derive from the idealizations introduced when describing a structure as a truss, e.g. the absence of shear forces or bending effect or the connections not transmitting the momentum. Since the motivations of such simplifications have never been presented to the apprentices and since their knowledge about structures is mostly grounded on real-life examples, the existence of elements that do not carry any load was considered to be odd. The analysis revealed also that the probability of wrongly identifying the force in a beam was related to its distance from the joint(s) where the external load were applied. Intuitively, the more a beam is far from the external force, the more difficult it should be to propagate the assumptions made so far and coherently work out a solution for the beam. Furthermore, in the interviews experts remarked that the task requires a large memorization effort. The labels that were used to annotate the forces in the beams were not helpful to mark the forces on the joints. The experimental task required extensive demands of the participants' working memory without providing an appropriate support.

Differences between the two experimental conditions arose from the analysis of the gaze data and the comparison with the experts. Our $H_{Visual\ Exploration}$ hypothesis was that the participants in the tangible group, compared to those in the verbal group, would have had a distribution of visual attention over the structures more similar to the experts' one. This would suggest a deeper understanding of the statics concepts, which would drive the gazes on the parts of the structures that are critical for the reasoning. What emerged for the analysis is the opposite situation: participants that received the verbal feedback behaved more similarly to the experts. They focused more on the joints and on those areas that experts looked at. The absence of relationship between these results and the learning outcomes should not surprise us, since the task was relatively short for consolidating the novel knowledge (Baylor, 2001). However, the focus on the joints could reflect the consolidation of a sort of intuition about the static equilibrium: in order to identify the forces inside the beams, it is necessary to analyse their interaction at the connections and how they compensate each other. This hypothesis might be supported by another result: the participants in the verbal condition had a higher percentage of statements about the forces in the beams. They tended to verbally remark to themself the forces while reasoning. Moreover, given the higher similarity with the experts' gaze distribution, they might have learnt to identify the critical features of the structures and to spot the differences between the scenarios of the exercises. Given the results of the experiments, how could we explain the apparent detrimental effect of the spring mechanisms and their manipulation? Even though the aim of the springs was to make visible the idea of axial forces, it probably led apprentices to think that the key to solve the exercise was to figure out how every single beam was reacting. Kriz and Hegarty, in their work on the effects of animations on learning (Kriz and Hegarty, 2007), described how in the absence of a consolidated prior knowledge of the domain, the learners' visual attention is directed toward distractive but not relevant stimuli. For low domain knowledge learners, bottom-up processes tend to influence more learners' attention than top-down processes, because the former are triggered by visual representations (e.g. animations, arrows, etc.) whereas the latter are regulated by the prior knowledge. In the tangible condition the manipulation of the spring mechanism throughout the whole intervention stage might have monopolized participants' focus at the expense of re-elaborating the pre-existing knowledge. On the contrary, in spite of the statics knowledge being homogeneous between the experimental groups, participants' reasoning in the verbal group could rely more on the physics principles they knew thanks to the absence of any external cue. Although the models were the same both conditions, the novelty effect induced by the presence of the spring mechanisms probably vanished because they could not be unlocked.

Before moving to the conclusions, it is worth mentioning the limitations we observed in this study. Several authors reported the issues related to the combination of think-aloud and eye-tracking protocols. Besides the individual differences in the ability to verbalize the reasoning process, it was observed in prior studies that participants perform slower when thinking aloud (Holmqvist et al., 2011). Nielsen and colleagues (Nielsen et al., 2002) showed that think-aloud also affects the rate of general exploration and learning processes since it takes resources from all parts of the cognitive system. Furthermore, the order in which the participants perform sub processes may change when thinking aloud (Davies, 1995). Nevertheless, we decided to use think-aloud, being aware of its disadvantages, but also of its advantages. In our case, the issues would be related mostly to the collection of data from the experts, since they were asked to think aloud during the whole intervention. Another potential weakness could be in the qualitative analysis of the think-aloud data, since, for practical reasons, the coding was performed by only one person. Moreover, the coding scheme was applied in a very dichotomous way and did not take into account qualitative differences.
The validity of the statics knowledge test as an assessment tool was questionable. Although the test was co-designed with a carpentry teacher and it was used in a pilot study, its reliability was not extensively checked. Nonetheless, given the absence of suitable alternatives, employing our test seemed an acceptable compromise.

5.5 Conclusion

This study explored the possibility of promoting statics reasoning skills by using interactive physical models. Their exploration and manipulation, along with the feedback offered by the elongation and compression of the members of the models, should have brought the participants to gain insights about the possible strategies to solve the given problems. However, the result indicated the absence of any learning benefit compared to the non-exploratory condition in which the physical models were rigid and the feedback was given verbally. This was consistent with previous researches (Han et al., 2009; Alfieri et al., 2011). Furthermore, the comparison with experts' data suggested that the employment of the spring mechanisms drove the participants' visual attention away from task relevant areas. Our conclusions should not imply a clear either/or choice between exploratory and non-exploratory or between hands-on and hands-off. Interactive physical models could be helpful as teaching tools and could also be helpful to learners that have a medium/high domain knowledge. However, this study offered, within its limitations, little support to the idea that hands-on experiences involving such materials could foster the deduction of statics principles in case of fragmented prior knowledge and without tutoring.

Concerning the development of our augmented reality system, the conclusions that have been drawn were:

- This study did not give any further support to the employment of spring mechanisms, also in light of the resources required to create them and to integrate in wooden models available in schools. The representation of axial forces by means of the spring metaphor could be implemented virtually, but it should be complemented by a visualization that could convey the idea of equilibrium at the joints.
- The augmentation should present a realistic and complete view of the effects of the loads on the structures. The system should display also bending effects, shear forces and displacements in addition to the axial forces. In this way, it would be easier to interpret, for example, the simplification introduced by modelling a structure as a truss.
- The timing and availability of the feedback would be controlled by the AR system rather than by the learners. In an authentic classroom scenario, a drawback of the spring mechanisms would be that students would playfully unlock them. This would cause a serious problem for teachers in terms of orchestration (Cuendet et al., 2013).

These considerations will be summarized in the next chapter together with the complete description of the AR system and its features as they appeared in the latest version.

Acknowledgement
The data from this study featured also in (Schwär, 2015, unpublished), although the analysis presented in this chapter has diverged on some aspects.

6 StaticAR: Qualitative Statics through Augmented Reality

This chapter introduces StaticAR, the AR application that we developed in order to bring qualitative statics in vocation classrooms. Although StaticAR is the result of several refinements brought during my PhD work, the following sections present only its final version in order to give to the reader an overview of the features offered by the system. The chapter is divided into two parts: the first section presents the technical features of the application and the augmentation of the learning resources in school context. The second section briefly presents how workplace experiences can be captured and become resources for the school lessons.

6.1 Technical Setup and Features

StaticAR is a cross-platform application[1] which includes features to analyse 2D and 3D trusses and frames. The interaction style is based on the magic-lens metaphor (Bier et al., 1993): a small-scale model of a structure is observed through the interface, which displays the results of the statics analysis superposed on the structure.
StaticAR has been developed using the Qt framework. The interface is tailored for handheld devices, like smartphones and tablets, and it does not require any other hardware features than those available in regular devices, specifically a rear camera and modest computational power[2]. Since the beginning, the design of StaticAR has been driven by the main constraint of our project, namely scalability. We wanted our solution to be widely adoptable in vocational classrooms. As pointed by Dunleavy and colleagues (Dunleavy et al., 2009), AR systems have shown difficulties in spreading within schools. Besides the scepticism towards the employment of new learning technologies and the inherent inertia in mutating the traditional teaching practices, there is also the problem of "practical" constraints. For instance, the need to purchase specific hardware that cannot be reused for general purposes, or the logistic issues related to moving from classrooms to computer labs. We tackled these problems by building StaticAR around the ideal scenario of a classroom in which teachers run their application on

[1] Running StaticAR on a platform requires compiling it for the target architecture.
[2] To serve as baseline reference, the application runs smoothly on a Samsung S5.

desktop PCs and project the visualization with a projector, while apprentices use their mobile devices to work at their desks.

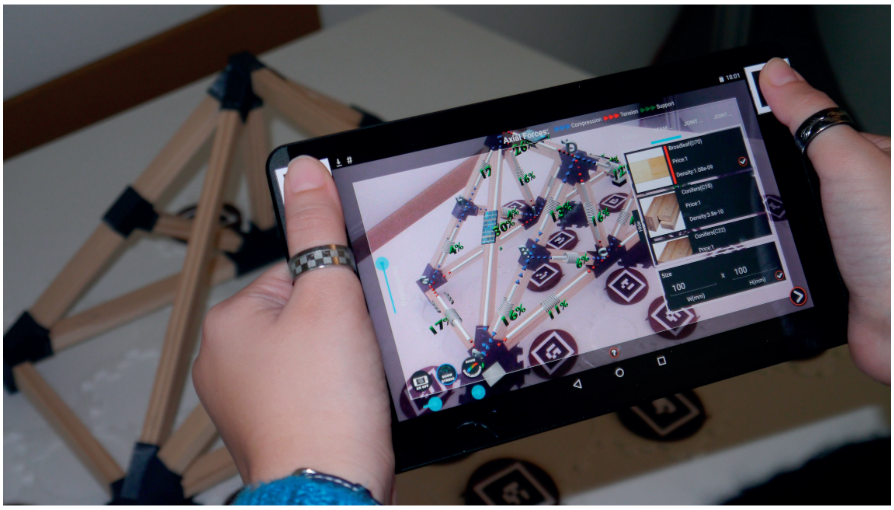


Figure 6.1 – StaticAR.

The Physical Layer

The physical substratum for the digital augmentation is given by the model of the structure under analysis. Typically, the model is a full small-scale representation of an authentic structure, like the timber models largely available in carpentry classrooms. We could have provided the structure as digital entity rendered, for instance, directly on a desk without any physical representation. However, we chose to augment the pre-existing practice rather than to ignore it following the suggestions given by the teachers. This choice was in our opinion the optimal way to adhere to three of the five design principles suggested by Cuendet and colleagues (Cuendet et al., 2013) to increase usability at classroom level: integration, awareness and flexibility.

Integration Employing physical models lowers the adoption barrier for the teachers, who already make use of them during their lectures. In addition, the usage of familiar materials as wooden models of plausible structures allows StaticAR to be in harmony with the professional identity, which is an aspect that cannot be ignored in the design of technology for VET. In one of our meetings with the carpentry teachers of the *Berufsbildungszentrum Bau und Gewerbe* school in Luzern, the teachers stressed the point that apprentices' knowledge is deeply contextualized in their professional practice. Thus, apprentices might exhibit difficulties in working with extraneous materials, like commercial kits that use metal structures.

Awareness Even though the application does not allow teachers to monitor students' progresses during the exercise, the presence of the physical structures provide an immediate information about which structure the students are analysing. During collaborative activities, it is likely that the physical model becomes the target of students' deictic gestures and direct manipulations. Thus, teachers can readily follow students' discussions and intervene to provide feedback.

Flexibility Teachers could decide to split the apprentices in groups and let them work on different structures and different activities according to their levels. Since the application runs on mobile devices, the only preparatory step would be arranging the structures in the classroom. Moreover, in case of unexpected events, e.g. low battery charge, students can exchange devices and keep working.

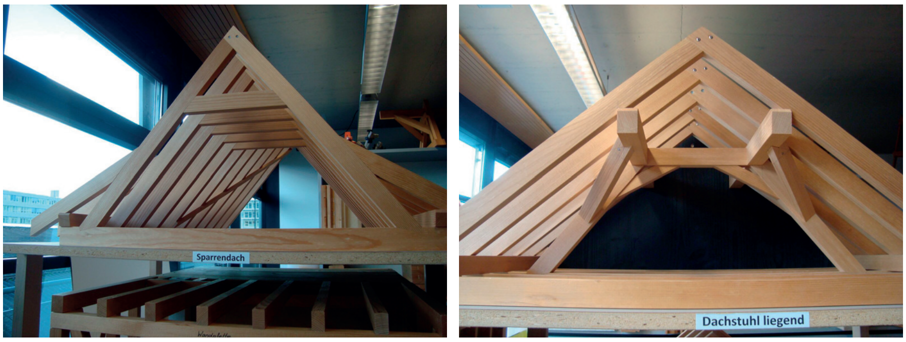


Figure 6.2 – Examples of roof models available in carpentry schools.

Visual Detection of the Structure

Regarding the AR tracking and pose estimation, the visual estimation is based on the detection of some fiducial markers rather than on the detection of a physical structure. The elements of the structures, typically made of wood, do not provide visual features suitable for detection. Although some authors proposed solutions to detect and track texture-less objects (Tamaazousti et al., 2011; Hinterstoisser et al., 2012; Wang et al., 2017), these methods are not robust yet to be used in authentic settings like classrooms. Thus, we preferred employing fiducial markers, specifically the vision methods provided by the library ARToolkit v5 (Artoolkit). The markers are placed on a hexagonal grid on which the physical model could be arranged. The hexagonal tiles have 52mm long edges, vertical (flat-topped) orientation and a circular socket at the centre of the tile having a 70mm diameter which can host a fiducial marker (Figure 6.3). The main advantage of using hexagonal tiles is that the topology that they form is well defined. We could exploit the mathematical properties of hexagonal grids to recognize any arrangement of fiducial markers. From the users' perspective, this means that users can freely create a connected layout and can generate a configuration file which includes the positions of the markers. A small utility has been developed to help the user in creating the configuration file starting from a top-view picture of the grid. The utility detects the markers and allows users to define the origin of the x-y reference system, to change the orientation of the axes and to add/remove fiducial markers from specific positions (Figure 6.4).

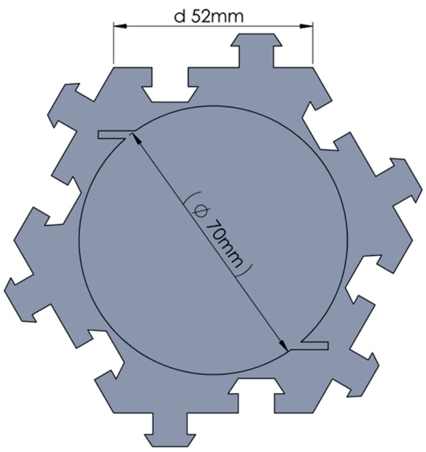
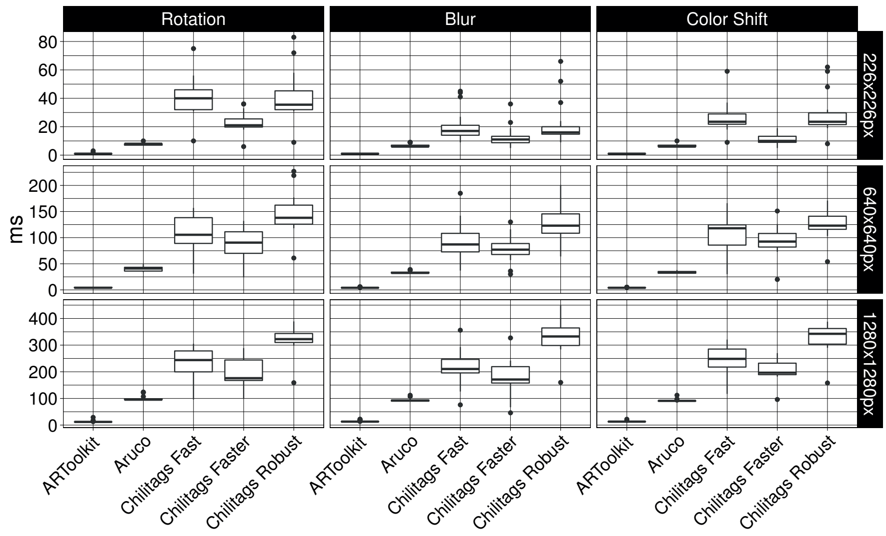


Figure 6.3 – Hexagonal tile.

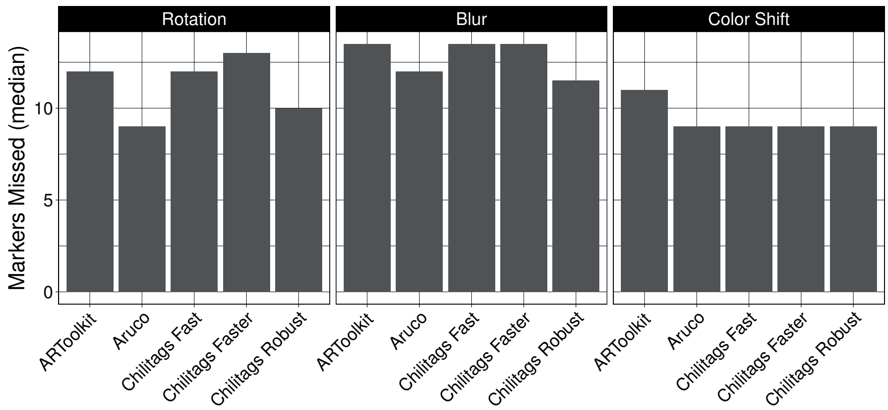
Figure 6.4 – The utility to create the configuration file containing the positions of the fiducial markers.

We chose ARToolkit after comparing the library to other two popular C++ open-source alternatives, Aruco and Chilitags (Garrido-Jurado et al., 2014; Bonnard et al., 2013). Aruco is a detection-only library, meaning that it does not implement any tracking of the markers between successive frames which could reduce the processing time per frame. Chilitags is a very versatile detection library which optionally includes tracking features. In our comparison we used the three levels of detection accuracy that are available in Chilitags, namely faster, fast and robust[3]. The input image contained 24 markers, 12 of which were made difficult to detect due to bad borders (Appendix C). The comparison included three types of test (Figure 6.5a columns), each of the three including 20 iterations. The *Rotation* test simulated fast movements between the frames. At each iteration the image was rotated 90 degrees clockwise. The *Blur* test simulated the condition in which the camera is out of focus. A Gaussian blur with a 7x7 kernel was applied to the image. Lastly, in the *Colour Shifting* test, the white color of the image was converted to grey (150), which created a low contrast similar to the case of poor illumination. Each test was run for three different resolutions (Figure 6.5a rows). The results showed that ARToolkit required less computational time than its competitors in all the tests. In terms of missed markers (Figure 6.5b), Aruco performed better than the other two libraries, which achieved comparable performances. In summary, considering the better time performance of ARToolkit and the small difference in the number of missed markers between Aruco and ARToolkit, we decided to employ ARToolkit in StaticAR.

[3]The level faster does not perform corner refinement and subsampling of the input image; the level fast performs only corner refinement; the level robust performs both the aforementioned steps.



(a) Time performance.



(b) Missed Markers.

Figure 6.5 – Comparison between marker detection libraries.

Statics Analysis Core

The statics analysis core is a customized version of Frame3DD, an open-source application released under GPLv3 license (Gavin, 2010). The software has been developed to perform the static and dynamic structural analysis of 2D and 3D frames and trusses with elastic and geometric stiffness. Even though the implementation considers the joints to be fully moment-resisting and the mechanical properties of the beams to be uniform in all orientations (isotropy), the errors induced by these assumptions are negligible for the purpose of StaticAR. The original version of the code is not provided as a library. The interface is command-line based and it outputs the results of the analysis via terminal and text files. Therefore, we kept only the code of the analysis kernel and implemented the user interface according to our needs.

The structure under analysis is loaded from a text file following the format shown in Figure 6.6. The first value is the scale factor between the actual dimension of the structure and the small-scale structure. The next part defines the nodes of the structure (joints). The global Cartesian coordinate is OpenGL-like, right-hand and having the y axis pointing upwards. Displacement restraints (R_x,R_y and R_z) and rotational restraints (R_x^m,R_y^m and R_z^m) can be specified for the nodes in order to provide supports to the structure. Lastly, the format lists the beams with their related extreme nodes, the rectangular section, the materials' ID and the rectangular section of each beam in the small-scale physical model. The local coordinate system for the beam is also right-hand but it has the local x axis along the beam length. The file format can specify multiple structures too. For instance, in case of two structures the nodes and the beams simply form a graph having two different connected components.
Concerning the materials, similarly to the structures, a material is defined through a text file which specifies the material's ID, its name, a thumbnail and the mechanical properties that determine the structural behavior.

StaticAR implements the following four types of load that can be applied to the structure:

Gravity Load is uniformly-distributed load acting on all the elements of the structure. By default, the gravity is set to the constant value $9.8m/s^2$;

Nodal Loads are concentrated loads applied to the joints. They are defined by the three components of the force along the global x, y and z axis;

Uniformly-Distributed Loads are loads applied all over the length of a beam. These loads are defined by the load per unit length along the local x, y and z axis;

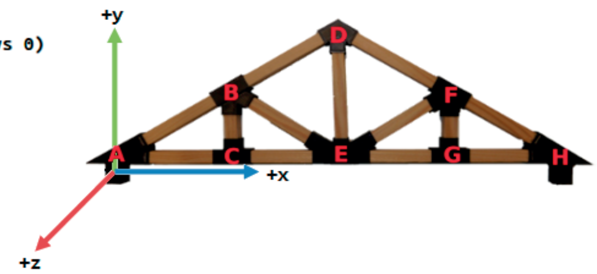
Trapezoidally-Distributed Loads are similar to the uniformly-distributed loads, except that they are applied over a partial span of the beams. A trapezoidally-distributed load is defined by its extent, by the start and the end locations on the beam and by the force vectors at those locations.

As soon as the configuration of the structure changes, because, for instance, a load is set or removed, a new analysis is performed. The kernel outputs the reaction forces and momenta for each supported joint. For each beam, the results include the values of the forces and the momenta acting at any segment of length 10mm of the beam and the displacement of the segments. From these quantities, it is possible to derive the amount of stress which the beams are subjected to. We distinguish four types of stresses: axial, due to the axial forces (tension and compression); shear, due to vertical and horizontal shear forces; bending and torsional, due to respectively bending forces along the local y and z axes of the beam and to the torque along the local x. The ratio between the stress in the beam and the maximum stress allowed by the resistance of the material defines the *relative stress*. When the relative stress in a beam exceeds the value of 1, the beam cannot sustain the load and it is considered to fail. This approximates the rules used for structural safety check available in (Wachter et al.,

```
0.1     # Scale factor between tangible model and real model
        # (real models are usually in the order of meters)
        # (it affects only the position of the joints)

8       # Number of nodes

# Node Name, x, y, z, dim(always 0)
A, 0, 0, 0, 0
B, 1170, 682.6, 0, 0
C, 1170, 0, 0, 0
D, 2340, 1365.2, 0, 0
E, 2340, 0, 0, 0
F, 3510, 682.6, 0, 0
G, 3510, 0, 0, 0
H, 4680, 0, 0, 0
```




```
8 # Number of reaction at the nodes

# Node Id,Rx,Ry,Rz,RMx,RMy,RMz

0, 1, 1, 1, 1, 1, 0
1, 0, 0, 1, 1, 1, 0
2, 0, 0, 1, 1, 1, 0
3, 0, 0, 1, 1, 1, 0
4, 0, 0, 1, 1, 1, 0
5, 0, 0, 1, 1, 1, 0
6, 0, 0, 1, 1, 1, 0
7, 0, 1, 1, 1, 1, 0

13 # Number of beams

# Beam name, extreme 1, extreme 2, width, height,
# material ID, tangible width, tangible height
AB, 0, 1, 25, 50, default, 0, 0
AC, 0, 2, 25, 50, default, 0, 0
BC, 2, 1, 25, 50, default, 0, 0
BD, 1, 3, 25, 50, default, 0, 0
BE, 1, 4, 25, 50, default, 0, 0
CE, 2, 4, 25, 50, default, 0, 0
DE, 4, 3, 25, 50, default, 0, 0
DF, 3, 5, 25, 50, default, 0, 0
EF, 4, 5, 25, 50, default, 0, 0
EG, 4, 6, 25, 50, default, 0, 0
FG, 6, 5, 25, 50, default, 0, 0
GH, 6, 7, 25, 50, default, 0, 0
FH, 5, 7, 25, 50, default, 0, 0
```

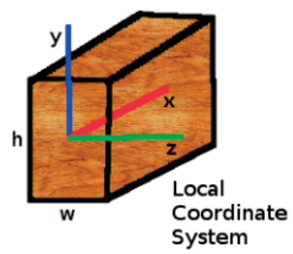


Figure 6.6 – Example of configuration file describing a structure.

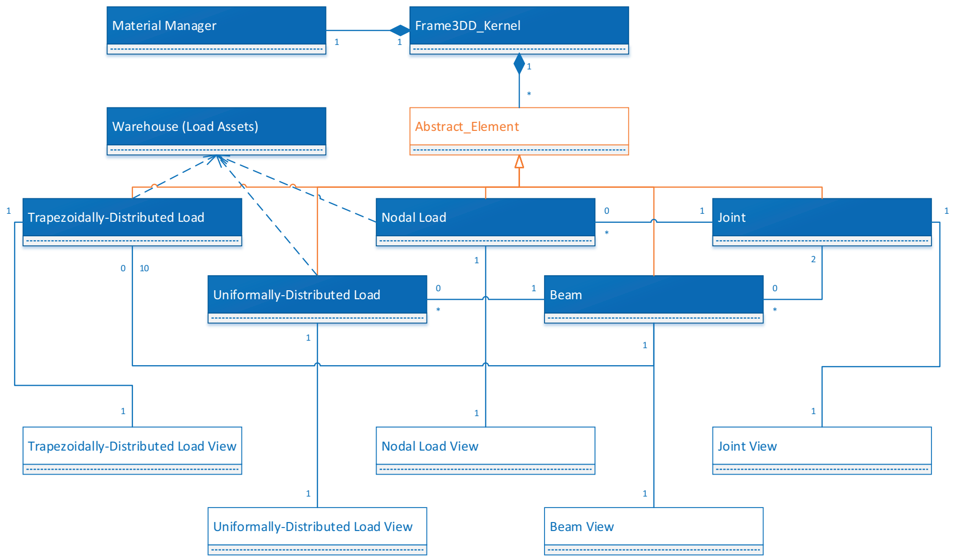


Figure 6.7 – Class diagram of the entities constituting StaticAR. The model classes are depicted in blue (top) whereas the related view classes are in white (bottom).

2000, Chapter 5). The current version of StaticAR does not implement the stresses caused by compression or tension forces that are perpendicular to the grain of the timber beam, since it would have required the modelling of the timber connections.
Figure 6.8 shows the benchmark of the kernel core ran on a Samsung S5 device. The synthetic structures used for the test had the topology of a complete graph with an even number of nodes ($N \in \{1..32\}$) and two supports. A nodal load was set on each node, whereas a trapezoidally-distributed load was set on each beam. The test was repeated 10 times for each structure. The red line represents the time required to run the analysis without outputting the results[4]. The cyan curve includes the time overhead for updating the graphical content[5]. The overhead is mostly due to the fact that no parallelization is implemented in the current version. The system response remains acceptable below the 150 beams, which is largely sufficient for our educational application, having a processing time inferior to one second.

Lastly, a complete description of both the material properties and the mechanical ones, the quantities returned by the kernel and the formula used to derive the stresses are listed in Table C.1, Table C.2 and Table C.3 in appendix C.

[4]Quadratic curve, $\beta_1 = -12$, $\beta_2 = 3.2$, $\beta_3 = 7.3$, $R^2 = 0.99$
[5]Quadratic curve, $\beta_1 = 267.7$, $\beta_2 = -7.8$, $\beta_3 = 0.06$, $R^2 = 0.99$

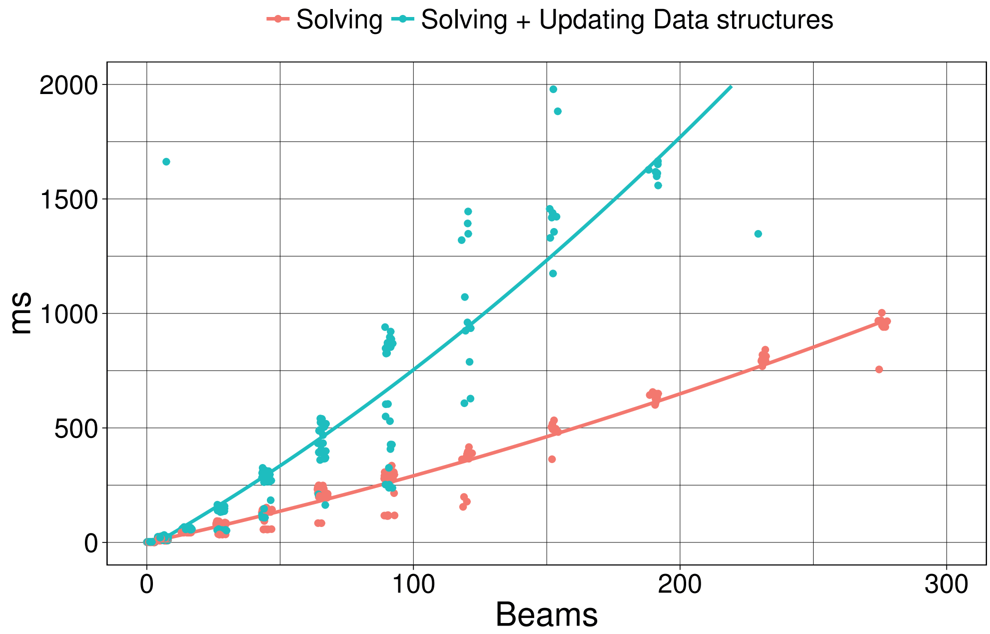


Figure 6.8 – Frame3DD benchmark.

Virtual Content

Most of our energy went into designing the visual representation of the core output, following the primary design principle of conveying a qualitative description of the behavior of the structures. The default virtual content of the augmentation is shown in Figure 6.9.

A grey rod with a spring is placed at the centre of each beam of the structure. The joints are depicted by spheres and labelled with uppercase letters. The panel on the right defines the main UI area. The area includes several tab views from which users can access the functionalities of the interface or can get instructions during the learning activities. Among these tab views, three of them allow for modifying the statics configuration:

Catalogue This tab view lists the available loads which are shown by their thumbnails and weights (Figure 6.10a). The loads are loaded from text files which specify the physical properties (weight, extent, etc.) and the visual appearances (mesh file, texture file and thumbnail). Uniform loads can be applied only on beams, whereas the others can be applied on both joints and beams, becoming respectively node loads or trapezoidal loads. In order to add a load on a beam or a joint the user selects the element, selects the load and then clicks the button to apply it. The loads are considered to be anchored to the elements they are positioned on and they exert a force always vertical to the structure.

Beam Materials This tab view allows users to change the mechanical properties of the beams (Figure 6.10b). A list of materials is available, displaying the name of the material, the

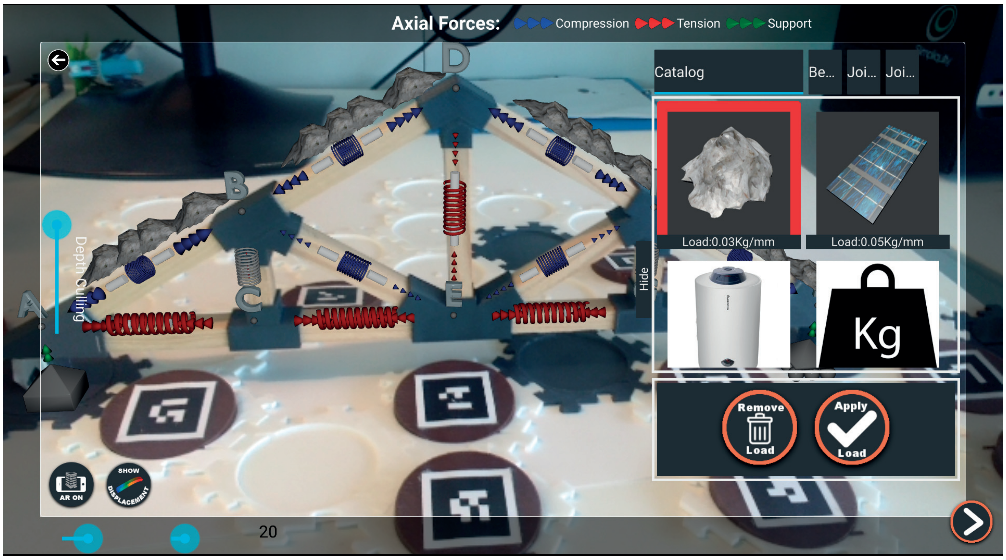
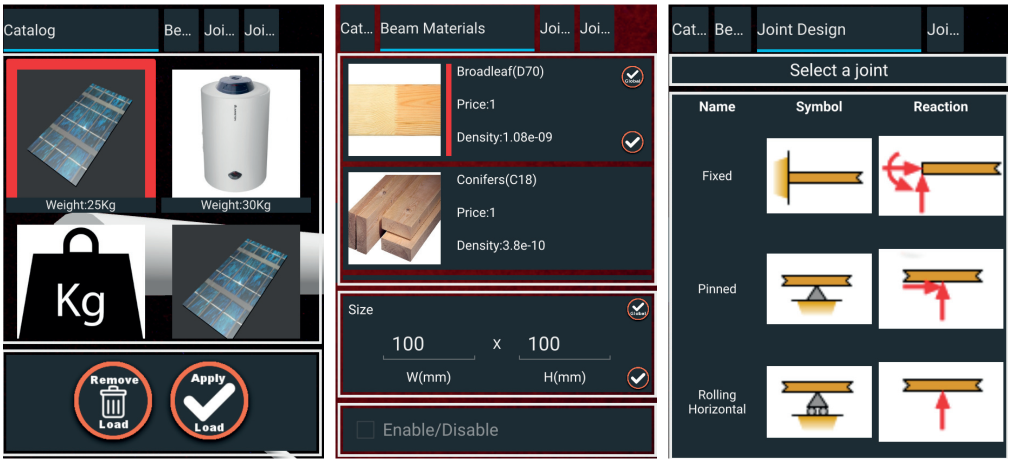


Figure 6.9 – The main augmentation displayed in StaticAR.

optional price and the density. The other informations, for instance Young's modulus, stress limits etc., are not displayed. We wanted to leave the material description as close as possible to the ones apprentices are used to. For example, the labels available in timber shops report the name of the material usually followed by the hardness of the timber. The labels summarize the physical properties that can be accessed online or on the carpentry handbooks by the apprentices. By including every physical property in the interface, it would have appeared too cluttered and it would have introduced some notations that usually are not relevant for the workplace practice.
From the same view, users can also disable the beams or change their width and height.

Joint Design From this view it is possible to choose between three types of supports for the joints: *pinned*, *roller* and *fixed* (Figure 6.10c). These supports are abstraction of three common types of connections that link a structure to its foundations or to load-bearing elements. The *pinned* connections resist force along three axes, whereas the *roller* supports resist only vertical forces, which are those along the y-axis in our reference system. Both supports do not resist to moments. On the contrary, the *fixed* connections resist to both forces and moments.

As regards the augmentation of the structure, when loads are applied on the structure, the springs on the beams expand or get compressed according to the type of axial forces acting in the beams, which could be either tension or compression. The type of force is also conveyed by the color of the spring which turns red for tension and blue for compression. The elongation of the spring is linearly proportional to the ratio between the peak axial force in the beam and the maximal axial force in the structure. Whenever the force is close to zero, the spring does not elongate and its color remains grey. It is important to notice that the axial stress does not affect the elongation, hence the spring representation is independent from the material of the beam



(a) Catalogue Tab (b) Beam Materials Tab (c) Joint Design

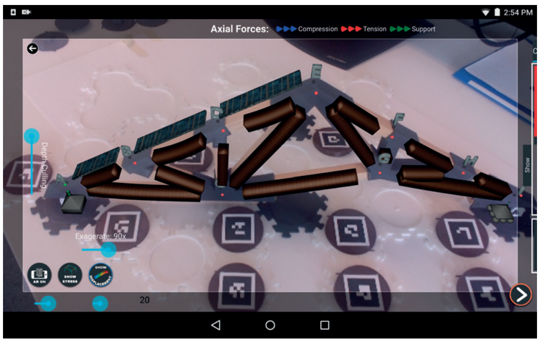
Figure 6.10 – The tab views for editing the loads, the property of the beams and the supports at the joints.

or from its section. The reason for this choice is that the spring elongation should convey the magnitude of the force qualitatively, thus making possible the comparison between the forces acting in different beams. In addition to the springs, the axial forces are also depicted by three arrows at the extremes of the beams. The color of the arrows changes as for the springs, red for tension and blue for compression. The arrows depict the axial force applied by the beam to the extreme joints. The size of the arrows is scaled according to the same ratio we used for the spring elongation.
Springs and arrows are complementary representations of the same concept. The springs convey the effect of the force on the beams, whereas the arrows convey the reaction of beams on the joints. The notion of action and reaction might be taken for granted by people with a scientific background, but the fact that “When the beam is compressed it pushes against the joints to keep the equilibrium” is not trivial and does not belong to the set of intuitive physics concepts. When looking at a particular joint, the arrows from the connected beams form a quasi-force diagram of the node (although non-axial forces are neglected) from which it is possible to observe how the equilibrium is reached.

The augmentation described so far is mostly showing the effect of axial forces, ignoring the shear and bending components. The reason is that most of the structures relevant to carpentry training are trusses, in which the beams can only be in tension or in compression. However, a complete visualization of all the forces acting on a joint, axial and non-axial, could be accessed through the *Joint Analysis* view in the panel on the right (Figure 6.11a). From the tab, the contributions of the beams and support (if any is present) can be activated and deactivated. The activation of one contribution changes the position of a sphere located around the joint. When the forces sum to zero (the equilibrium condition) the sphere is centred at the joint and it turns green. Otherwise, the sphere moves according to the direction and magnitude of the resultant force and its color ranges from red to green based on how far the node is from the equilibrium.

The global deformation of the beams and the displacement of the joints could be visualized directly on the structure (Figure 6.11b). For each beam, a mesh having the width and the height specified by the cross section of the physical beam is created[6]. The mesh is divided along its length into segments. The segments are displaced from the natural axis and they are rotated according to the segment displacement vectors computed by the statics core. In case the effect of the loads is not sufficient to create visible deformations, users can "exaggerate" it by a factor up to 500 times. This highlights how the structure deforms and how it diverges from its original configuration.
Lastly, the three types of relative stress for the beams (axial, bending and shear) are shown as percentages of the maximum stress that the elements can sustain (Figure 6.11c). When the stress value exceeds the 50% limit, a sound like wood creaking is played, whereas when the value exceeds 100% a crash sound is played.

(a) Joint analysis tool.



(b) Global deformation of a structure.

(c) Stresses in the elements of the structure.

Figure 6.11 – Complementary representations of the forces acting at a joint, global deformation and stresses in the beams.

[6] This information is included in the configuration file of the structure.

6.2 Creating Resources for the 'Erfahrraum' Model

As explained in the previous section, the resources available in StaticAR (loads, materials, fiducial marker configurations and structures) can be shared as files, for instance through the Realto platform. Among these resources, the structures are the most relevant artefacts to feed the 'Erfahrraum' flow and they close the loop between workplace and school. In order to facilitate the creation of the files that define the structures, we implemented a small mobile application that allows apprentices and teachers to draw 2D structures and to save them in the proper format.
The editing view of the application is shown in Figure 6.12. Apprentices or teachers capture a picture of the structure and set it as background upon which the joints and beams are drawn. The interface allows the users to define the following geometrical constraints and relationships among the elements: horizontal, vertical, equal length, parallel, perpendicular, angle between beams. The constraints are solved using the library SolveSpace, a numerical constraint solver distributed under the GPLv3 (SolveSpace). The sketches are exported as structure files and saved locally, hence they can be opened and modified at any moment to create alternative structures.
Both the sketches and the structure files become artefacts for the 'Erfahrraum'. The choice of the resources that are 'relevant artefacts' is part of the post-selection activity in which both the teachers and the apprentices are involved. After this stage, the only step left to use StaticAR is the creation of the small-scale models which are manufactured in the workshops of the vocational schools.

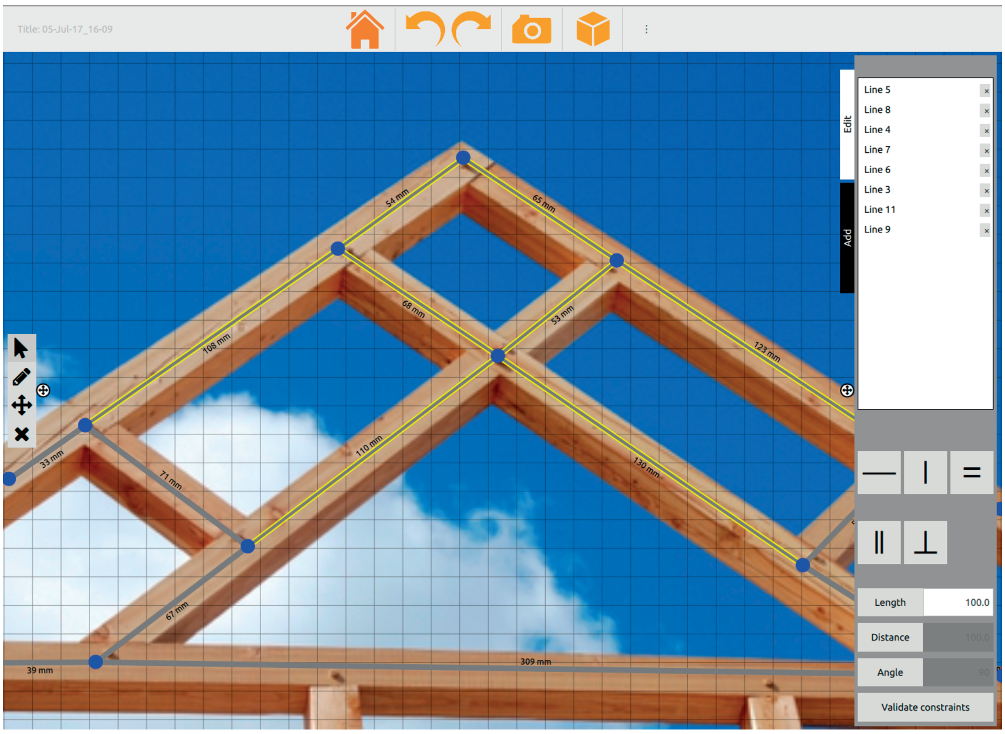


Figure 6.12 – Application for drawing structures at the workplace.

6.3 Conclusions

This chapter has described StaticAR and the way we implemented the 'Erfahrraum' by using it. The goal of the chapter was to describe the details of the implementation and the available features as they are in the last version of the application. The application has been used in the two experiments that are presented in the following chapters. The first study investigated the role of shifting the visual attention between the physical realm (small-scale models) and the digital one. The last study concerned the representations of the forces through springs and arrows. It focused on how the two representations support the emergence of a qualitative understanding of the principles of statics. In both studies, the interface of the application presented some differences compared to the version presented so far. Each chapter will describe these differences and how the experimental activities were implemented.

7 Study III: Shifting the Gaze Between the Physical Object and Its Digital Representation

7.1 Introduction

In the previous chapter, the presence of a physical structure as substratum for the digital augmentation was motivated as a way to integrate StaticAR almost seamlessly in the carpentry classrooms. Nevertheless, the reader might have noticed that the physical structure is not functional to the interaction with the AR system. None of the actions available in StaticAR were triggered by gesture interaction or tangible controls and, furthermore, the pose estimation was performed by tracking the hexagonal grid rather than the actual structure. The interaction through the device is common in handheld magic-lens systems, in which real-world objects are considered to be the background upon which the virtual content is overlaid and the user's attention is focused on the device rather than on the target object of the augmentation. If the interaction does not involve the direct physical manipulation of that specific target object, it is a fair assumption that such object could be replaced by a high-fidelity digital rendering. What is the added value of having a real object fully matching its digital representation? A way to investigate the role of the physical layer per-se, not just as background for the augmentation, is to look at the moments when the users look directly at the physical layer and bypass the screen instead of looking through it. This chapter presents an eye-tracking study centred on the occurrence of the shifts of visual focus from the augmenting device to the physical reality. The experimental task consisted in solving qualitative problems about the statics of structures through visual inspection by using StaticAR. The nature of this study was exploratory, since very few quantitative works explored the factors influencing the shift of attention between the physical and digital realms. To some extent the point in question recalls the physical correspondence dimension that was the focus of our first study. However, differently from the TUI setup presented in that study, in the magic-lens interaction the physical layer does not act as UI control. In order to give sense of the research hypotheses driving the following study, this chapter begins with a review of the related works from which the hypotheses were derived.

7.2 Research Hypotheses

Learning Domain: Physicality for Compensating Low Spatial Skills As discussed in the related work chapter, the basis for the adoptions of AR in STEM education could be found in their ability to sustain spatial reasoning and to compensate for low spatial skills better than traditional materials and than immersive virtual environments (Shelton and Hedley, 2004). However, some authors pointed out that the level of spatial ability has implications on the attitude of learners towards the type of representation, resulting in low spatial users preferring simple representations over complex 3D ones (Huk, 2006). Here is our first hypothesis:

$\mathbf{H}_{Spatial-Skills}$: The amount of attention shifts between the physical and digital realms is influenced by users' spatial ability. High-spatial users would perform fewer transitions.

Physical-Digital Switching in HCI research As regards collaborative AR environments (eg. tabletop), having small-scale physical models on which to jointly focus has been shown to facilitate conversational grounding, to promote negations about interface resources and to achieve a balanced level of participation in exploratory learning tasks (Schneider et al., 2016). However, to our knowledge, few works explicitly focused on the switch of attention from digital to real context in individual augmented reality setups. These works can be divided in two categories: switching for compensating AR flaws and switching for accessing a complementary representation.

A shift may signal the need for a pause from the AR experience that could serve to mitigate some of the perceptual issues present in augmented reality (reviewed in Kruijff et al. (2010)). Physical fatigue, depth ambiguities in the 3D rendering or instability in the AR tracking and pose estimation might lead to unpleasant discontinuities in the user's experience. Those could be minimized by shifting the attention from the device to the surrounding settings. In the domain of map exploration using magic-lens systems, Čopič and colleagues (Čopič Pucihar et al., 2014) found that users switched between the magic-lens device and the large background map in order to double check their solutions. The participants mostly used an "image comparison" strategy in order to merge the tablet view and the background map, which consisted in searching landmarks present on both the magic-lens device and the large map. The authors made the hypothesis that such behavior resulted from users' lack of confidence in the magic-lens transparency and that the implementation of user-perspective rendering rather than device-perspective rendering reduces the occurrence of such event. Veas and colleagues noticed that users experience physical fatigue when holding up a device for more than 3-5 minutes and, consequently, they need to interrupt the interaction with the digital augmentation (Veas and Kruijff, 2008). Thus, the authors proposed to overcome such issue by optimizing the ergonomics of handheld devices. Lee et al. (Lee et al., 2009) proposed the Freeze-Set-Go interaction method which consists in freezing the AR scene during the interaction to increase the user's accuracy. As a consequence of such interaction technique, the authors reported the need of users to continuously refer to the real-world scene to maintain the match with the frozen digital view.

Among the AR flaws that might cause a switch towards the physical layer, we decided to build our next hypothesis around physical fatigue and registration issues since those are common problems across heterogeneous AR systems.

H$_{AR-Faults}$: Compared to having the device on a stable support, holding the device with hands and the consequent instability of the augmentation (e.g. jitter, "shaky" view) cause an increase in the gaze shifting.

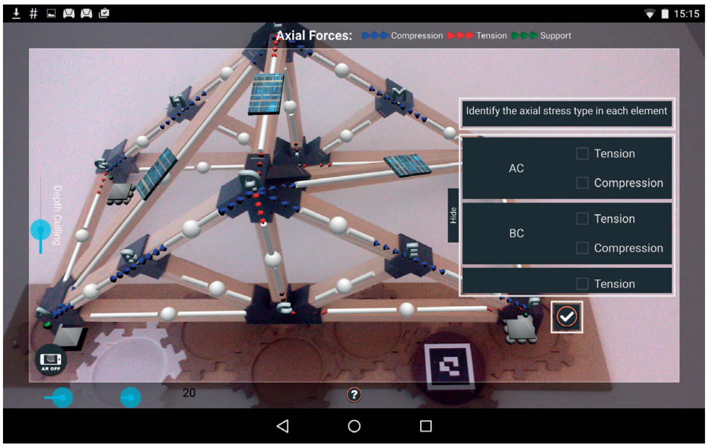
The attention switch between information sources is usually considered to negatively affect the users' experience due to the overhead of changing the frame of reference (Tang et al., 2003). However, switching could lead to a higher performance or to effective strategies when accessing the same information from multiple representations. In the context of magic-lens system for exploring maps, Rohs and colleagues (Rohs et al., 2009) investigated the effect of item density on the switch of focus between background map and virtual content on screen. In this study, a camera phone was used to find points of interest on a background map which was displayed on a LCD screen. The authors found that the switch from the AR phone to the background occurred in order to quickly locate items and move the phone on them. However, as the map density increased, the information on the background map became cluttered and the subjects refrained from shifting their attention to it, preferring the examination of the map through the magic lens device. In AR applied to navigation in outdoor environments, Veas et al. (Veas et al., 2010) relate the switch of attention between the device and the surrounding area to the spatial awareness of the user. The authors define spatial awareness as "a person's knowledge of self-location within the environment, of surrounding objects, of spatial relationships among objects and between objects and self, as well as the anticipation of the future spatial status of the environment". The study investigated the effect of different representation techniques on the ability of users to understand the spatial relationship between multiple camera placed in different locations around them and to draw a map of the area. The results showed that, regardless of the representation technique, the users had to directly observe the environment in order to infer the spatial transformations among the camera and complete the drawing task. Whether this result holds for indoor environments and, more specifically, for the magic-lens system is not clear. According to Shelton and Hedley (Shelton and Hedley, 2004), AR should leave intact the users' proprioception of themselves while navigating in physical space. If the switch of visual attention plays a role in preserving spatial awareness, it should be possible to identify a relationship with the user's position or navigation.

H$_{Spatial-Awareness}$ The shift of visual attention depends on features related to the way users move around a physical objects and navigate the space. For example, velocity, acceleration or the user's position.

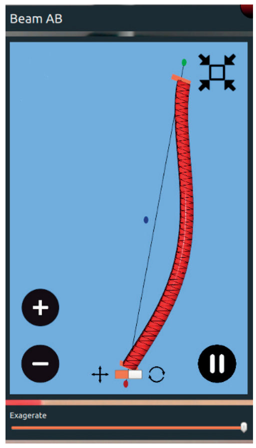
7.3 Experimental Setup

7.3.1 Compression-Tension Task

The inspection of a structure subjected to loads is one of the common tasks students have to face while learning statics and analysis of trusses and frames. The compression-tension task consists of a series of exercises in which the participant is asked to identify which elements of a structure are under either compression or tension given a particular configuration of loads. Figure 7.1a provides an example of the exercise in which the three solar panels apply vertical forces to the structure. The exercise should be solved by only employing visual inspection, without using paper and pen, leveraging the intuitive understanding of the problem to find the solution to static equilibrium.



(a) Example of the trials from the experiment. The solar panels represent the loads. The axial forces of some beams are shown as hint to the problem.



(b) Deformation of a selected beam

Figure 7.1 – Compression-Tension Task implementation.

7.3.2 Experimental Conditions and Implementation

This study presented two experimental conditions: tablet-in-hands (TiH) and tablet-on-support (ToS). In TiH condition participants were holding the tablet with both hands (Figure 7.2a). The interface allowed them to freeze the current view and stop the real-time augmentation. In the ToS condition, the tablet was arranged on a movable goose-neck tripod and no freezing feature was enabled (Figure 7.2b). Both conditions were equivalent in terms of positions reachable by the participant. Furthermore, in both conditions, whenever the pose was not available for a frame, the virtual content kept the previous pose and remained visible. We would like to stress the fact that the interaction does not require any direct manipulation or observation of the physical structure. The rationale to compare the two conditions was related to the hypothesis $\mathbf{H}_{AR-Faults}$. We expected a larger amount of shifts in TiH condition, since

participants might experience fatigue or visualization inaccuracy (e.g. shaky view). Hence, they might decide to take a pause from the augmented reality, either working directly on the physical structure or freezing the device and performing transitions between frozen view and real-world objects in order to exploit different viewpoints.
The experimental task was implemented in StaticAR, running on an Nvidia Shield tablet with 8-inch display. The interface was similar to the one described in Chapter 6 except for the absence of the visualization of the global deformation, which was developed after the experiment as consequence to the feedbacks of the participants. In the version for the experiment, the deformation of a selected beam was shown in the right panel (Figure 7.1b). A button allowed the participants to take a picture of the current view and to freeze the augmentation.

(a) TiH condition. The tablet is hold by the participant.

(b) ToS condition. The tablet is attached to a goose-neck tripod having a wheels

Figure 7.2 – Experimental conditions.

7.3.3 Participants and Procedure

Thirty-five undergraduate students, including 11 females, from the first year of civil engineering school and architecture school of the École polytechnique fédérale de Lausanne took part in the experiment. The experiment took place at the very beginning of the semester, thus all participants had little or no prior knowledge of statics and structural behavior topics but some interest in them. In order to verify the relationship between spatial abilities and gaze shifting ($\mathbf{H}_{Spatial-Skills}$), each participant took the Vandenberg and Kuse's mental rotation test (MRT) of 12 questions to enable us to rank their spatial skills. The test lasted 3 minutes and the scores of a single item were weighted according to the level of difficulty found by Caissie et al. (Caissie et al., 2009).

During the experimental task the participants were asked to wear the eye tracking glasses. They started with a demo exercise to familiarize with the system, to explore the features of the interface and to make a trial. Once the participants felt ready, the experimental series began.

The series was composed of four compression-tension exercises on four different structures. The order of the four exercises was randomized across the participants. In each exercise the participants went through three stages:

Solve Loads of same weight were set on the structure beams and the participants had to find different types of axial stress acting in three beams (Figure 7.1a). The interface showed the axial forces of a small subset of beams as a hint to the exercise, whereas for the other beams such information was hidden. During this stage the participants were only allowed to freely navigate around the structure and touch it, but they could neither change the loads and the mechanical properties of the beams nor check deformations.

Verify The participants checked the correct solutions and compared them with their own answers. In this stage the axial forces of all beams were displayed, but no other function was available

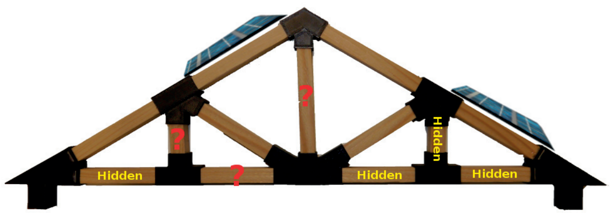
Explore This stage allowed the participants to use all analysis tools and design tools available in StaticAR in order to study different configurations of the loads and settings. No time limit was set for any exercise or stage.

The four structures were small-scale models of common roof trusses and frames from the carpentry context. The Howe is a two-dimensional truss characterized by the symmetry of the elements. The other two-dimensional structure was the Vault. Compared to the Howe, the left part and the right one are not mirrored, introducing more difficulty in the analysis of the internal forces. Both Howe and Vault presented a fixed support on the bottom-left joint and a rolling one on the bottom-right joint. The Gazebo and the Roof structures were three-dimensional structures having respectively rotational symmetry of order 6 and 2 with respect to their vertical axis. In the Gazebo structure the base joints were all fixed supports, whereas in the Roof structure two joints were fixed and the other two were rolling. In the four exercises, the difficulty of the task depended on the complexity of the structure rather than in the dispositions of the loads. The experiment was ran in such an environment where there was no other visual landmark besides the structure in the camera field of view. At the end of the experimental task, an informal interview was conducted to enquire about the AR experience and the participants' opinions on the role played by the physical structures.

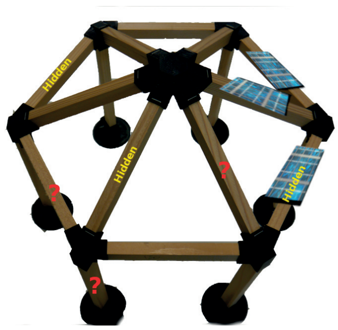
7.4 Statistical Analysis and Findings

All analyses were carried out using R v3.2 (R2016), using the package 'lme4' (Bates et al., 2015) to fit generalized linear mixed models (GLMM) and the package 'adhabitatLT' to analyse users movements and trajectories (Calenge, 2006). The features used to describe the navigation are the travelled distance and the residence time[1]. By considering the location of the structure as the origin of our reference system, we define zooming events as changes of the radial

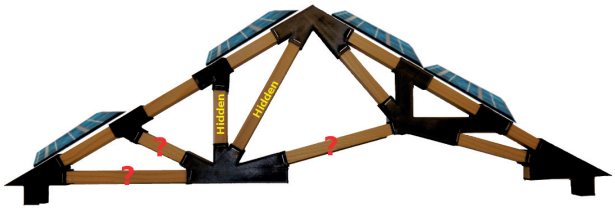
[1] The residence time associated to a particular place is a measure of the time spent by a participant within a certain radius of the place. In our setup the radius was 50mm, since above this value the point of view of the tablet changed meaningfully. This measure allowed to segment the participants' trajectories and to avoid considering small movements as changes of positions.



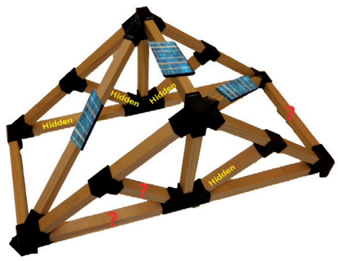
(a) Howe Truss



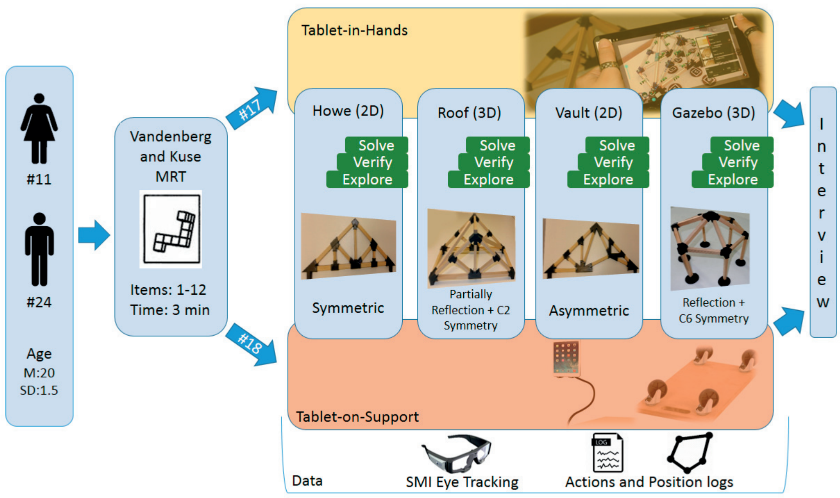
(b) Gazebo Structure



(c) Vault Truss



(d) Roof Structure



(e) The flow of the experiment

Figure 7.3 – Experimental materials and procedure.

coordinate that are longer than 100mm; whereas a change of point of view was defined as a change of the angular coordinate that measures more than 10 degrees. The eye-tracking terminology remains the same used in the previous chapters (see subsection 2.3.2). Fixations were categorized according to whether they landed either on the tablet or on the structures. We used two measurements to describe the gaze behaviour while looking at the physical structure: the number of fixations and the gaze duration. These variables correlate positively with the difficulty of the task and the difficulty of extracting or interpreting information (Jacob and Karn, 2003). We excluded from the analysis two participants, one from each condition, and data from one participant in ToS condition during the trial of the Gazebo structure due to technical problems in acquiring the data.

7.4.1 Descriptive Statistics

The average duration for each trial was 4 minutes and it did not differ significantly among the four trials (Table 7.1). Although average duration appears higher in the ToS condition, there was no significant difference between the conditions and the trials. The amount of correct

Table 7.1 – Average duration of the trials for each condition.

	TiH	ToS	Kruskal-Wallis H-test
Howe 2D	192s (SD 103)	224s (SD 111)	H(1)=0.927, p=0.33
Vault 2D	183s (SD 68)	217s (SD 113)	H(1)=0.388, p=0.53
Roof 3D	191s (SD 59)	246s (SD 116)	H(1)=1.973, p=0.16
Gazebo 3D	157s (SD 79)	224s (SD 223)	H(1)=0.308, p=0.57
	GLMM, $\chi^2(3)$=4.277, p=0.23		

answers given by participants in the compression-tension task did not differ significantly between the two conditions (ToS median 9, TiH median 10, W=111.5, p=0.164). Obviously, the level of difficulty was not the same among the four trials and the average scores achieved in the single trials were statistically different ($\chi^2(3)$=26.529, p<0.001). The pairwise post-hoc test revealed that the average score in Gazebo trial was significantly higher than the average scores in both the Howe and Vault trials (p<0.001). However, we did not observe any relation between the achieved scores and the gaze shifts.

The median number of gaze shifts towards the real structure was 4 (IQR:6.25). In terms of percentage of fixations on the real structure over total fixations, the median value is only 1.2% (IQR:6, Figure 7.4), meaning that looking at the physical structures is a rare event. The fixations occurred mostly in the *solve* stage rather than in the *verify* and *explore* ones (Figure 7.5).

The average duration of the four trials did not differ significantly, however the fixations on the structure were found to be significantly higher for both the trials involving the Roof and Vault structures (GLMM negative binomial, $\chi^2(3)$=14.59, p=0.002). On average, the gaze duration became longer as the task proceeded (GLMM, $\chi^2(3)$=7.60, p=0.005), but no significant difference was found across the four structures (GLMM, $\chi^2(3)$=2.457, p=0.48).
Figure 7.6 shows the heat-map of the positions participants took around the structures during the four trials. Those involving the Howe and Vault 2D structures presented low amount of navigation, characterized by users placing the tablet in front of the real world structure. In

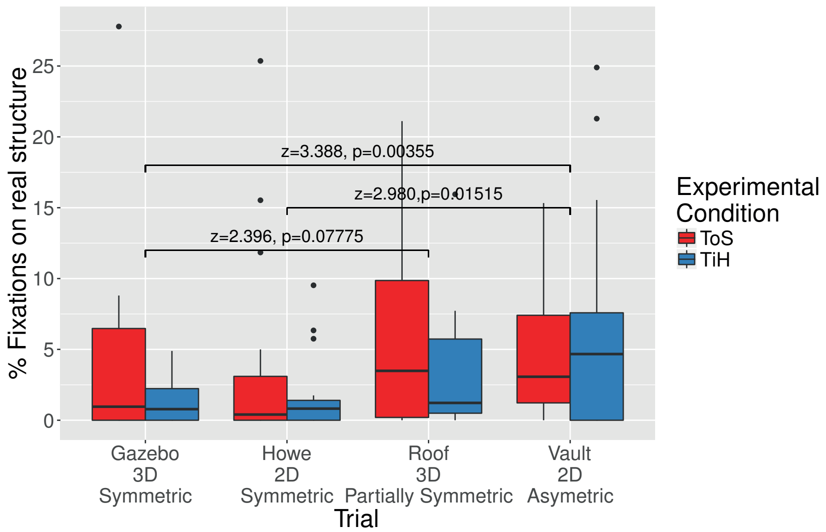


Figure 7.4 – Percentage of fixations on the real-world structures.

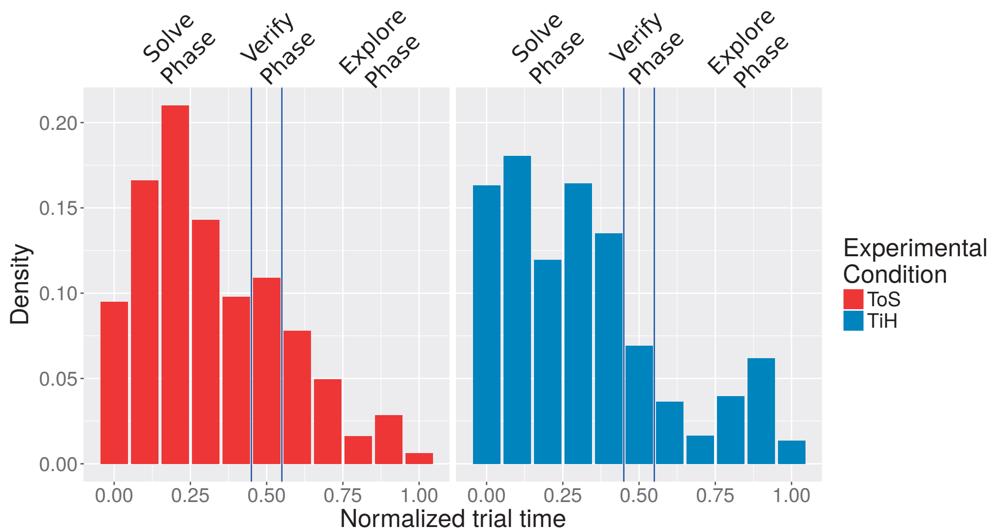


Figure 7.5 – Normalized histogram of the fixation on the structure with respect to the normalized trial time.

3D trials, the navigation was more uniform around the structures, presenting a significantly higher number of zooming and changing of point of view (GLMM, $\chi^2(3)$=49.09, p<0.001).

H$_{Spatial-Skills}$: Effect of Spatial Skills on the Gaze Shift The average MRT score was 11.89 ± 5.94 (out of 23) and it was not found to be different in the two experimental conditions (F[1,33]=0.38, p=0.54), indicating the absence of bias in the two experimental groups. The MRT score affected significantly neither the duration of the trials (GLMM, $\chi^2(1)$=1.312, p=0.25) nor the number of gaze shifts towards the structure (GLMM negative binomial, $\chi^2(1)$=1.422, p=0.23). Regarding the episodes while participants were looking at the structure, the average

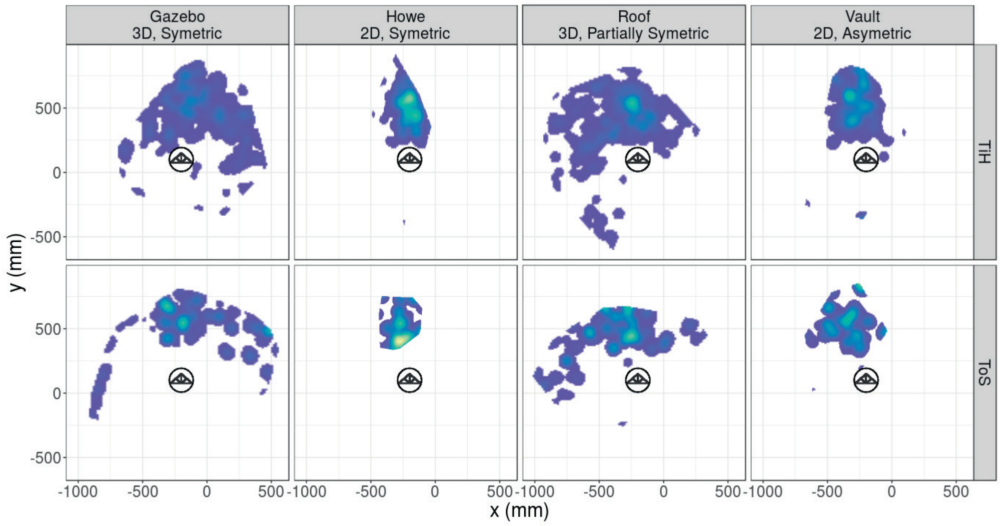


Figure 7.6 – Distribution of the tablet positions around the real-world structures.

length of such episodes did not depend significantly on the MRT score (GLMM, $\chi^2(1)$=0.189, p=0.66). Similarly, we did not find any significant effect due to MRT score on the navigation around the structures. Thus, we rejected $\mathrm{H}_{Spatial-Skills}$.

$\mathrm{H}_{AR-Faults}$: Effect of the Experimental Conditions on the Gaze Shift Although the average duration of the single trials is slightly higher in the ToS condition, no significant difference was found compared to the TiH condition. In the TiH condition most of the users did not use the freezing AR feature. We recorded only 34 events of view freezing performed by just 5 participants, and only 2 events were characterized by fixations on the structures. The experimental condition did not appear to significantly affect the number of fixations on the structures (GLMM negative binomial, $\chi^2(1)$=2.420, p=0.120). However, during the shifts, the gaze duration was on average 1822ms ± 170(SE) in the ToS condition whereas it was 777ms ± 229(SE) lower in the TiH condition (GLMM, $\chi^2(1)$=8.25, p=0.004). Hence, the participants in the ToS condition had longer span of attention towards the physical structure than the subjects in TiH. This might be related to differences in the process of memorizing the structures. Such differences, in turn, might be also related to the way the participants navigated around the structures in the two conditions. Although the areas covered by the participants in the two conditions were similar, the participants in the ToS condition had on average longer residence time compared to the TiH participants (GLMM, $\chi^2(1)$=6.11, p=0.01). Furthermore, the travelled distance increased in TiH condition by about 1160mm±312 (standard error, GLMM, $\chi^2(1)$=7.12. These results are also reflected in a minor number of both zooming events and changes of point of view events.

$\mathrm{H}_{Spatial-Awareness}$: Effect of Navigation Features on the Gaze Shift Spatial data were merged with the eye tracking events in order to retrieve both the positions occupied by the participants and the object they were looking at during the whole experiment. Figure 7.7 shows how the

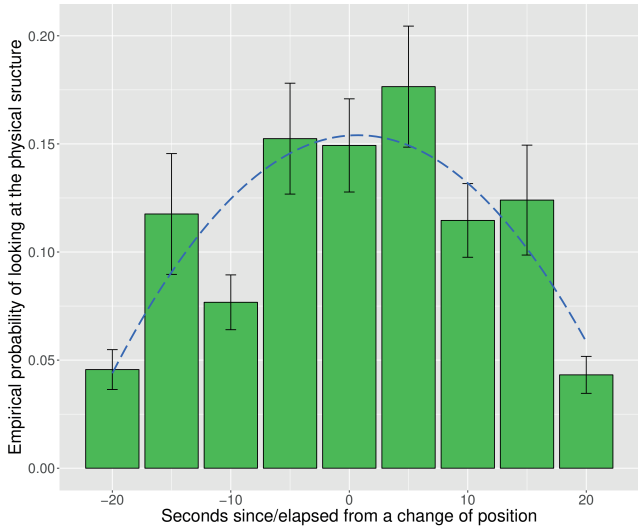


Figure 7.7 – Temporal distribution of the shift towards the physical structure in relation to the change of position. High density in the central part suggests a temporal proximity between changing position and looking at the structure.

shifts of attention towards the physical structure were distributed over time in relation to the change of position. On the horizontal axis, positive values indicate the time elapsed from the last change of position. For instance, the bin "10" includes the shifts happening in the interval from 7.5 seconds to 12.5 seconds after a change of position. Similarly, negative values indicate the time to the next change of position. For example, the bin "-10" includes the shifts happening in the interval from 7.5 seconds to 12.5 seconds before a change of position. High frequencies are associated to the central part of the plot, suggesting that looking at the real-world structure and changing point of view have a relationship. In order to validate such intuition, we built a GLMM with the residence time as continuous predictor. The model showed a decrease of the log odds of looking at the physical structure by -0.381 as the residence time increased (95% CI -0.445 and -0.315, $\chi^2(1)=141.85$, $p<0.001$). Thus, we built a second GLMM using speed as continuous predictor, which showed an increment of the log odds by 0.087 (95% CI -0.007 and 0.167, $\chi^2(1)=4.02$, $p=0.04$). The two models suggested a connection between changing position and looking at the structures.

Findings from the interviews

Regarding the device display, the participants found the tablet screen too small, especially because the exercise description filled a third of it, and they suggested to use a 10inch tablet. In "tablet on support" condition some participants felt to be constrained in the movements because the goose-neck support was too stiff, thus they avoided moving unless it was really necessary. Overall they were satisfied by the AR quality, even though seven participants in the TiH pointed out that the augmentation was "shaky". Regarding the trials, the participants felt the whole sequence to be of reasonable difficulty. The questions about the Roof and Vault structures were perceived to be more difficult due to the unusual shapes, which require longer time to get used to, and also due to the lower symmetry, which does not allow to transfer the reasoning done on one part of the structure to another. The participants expressed a range of considerations exhibiting coherence with the findings from the previous section[2]:

Useless or replaceable (N=12) The structure is an abstract mathematical entity and is analyzed as a system of equations. One or more pictures are sufficient since most of the spatial processing is done mentally. *"When I try to understand a structure, I don't think about it as a thing[...], it is just an exercise[...]. I don't think about going real life and simulating [the exercise scenario]."*. However, it was interesting to notice that typically those participants were aware of their spatial skills and they affirmed that the structure could be beneficial for people with lower skills.

AR Flaw Compensation (N=13) Shifting to physical model when the augmentation is noisy allows not to interrupt the reasoning process. Looking at the physical model disambiguates 3D rendering issues in case of self-occlusions or provides depth cues. *"[when it's shaking] I think it is more tiring to look at it on the screen than looking directly at the structure"*.. It was a shared opinion that real world structures provided depth cues in case of self-occlusion between the elements of the structure, especially in the Roof trial when several beams overlapped.

Navigation (N=6) The participants appreciated the ease and speed of navigation provided by the AR system compared to the traditional interaction styles based on mouse and keyboard. The physical structure acts as a spatial anchor, supporting the spatial awareness of the user. The participants who gave this explanation reported that they quickly glanced at the structure in order to decide the successive points of view.

External representation and tangible interaction (N=13) The physical structure offers a scaffold to the mental representation of the forces and the path of the loads. Eight participants preferred to directly manipulate the physical structure instead of just moving themselves around. Among those, 3 participants felt important to have the physical structure in order to be able to push it with their hands and observe the deformation at the joints to get "physical impression". *"I think it is important to have the structure, because it is easier to picture in my mind how and in which way the forces go when I press here". "[when acting directly on the structure] you can feel what happens in the wood. It is harder if one only has the display."*

7.5 Discussion

Regarding the MRT score, the analysis did not show any effect between the user's mental rotation ability and the number of visual references towards the physical structures or the

[2]The number in brackets indicates the number of participants who shared that specific point of view.

Figure 7.8 – Participants physically interacting with the structures.

length of these visual references, thus we reject the hypothesis $\mathbf{H}_{Spatial-Skills}$. We consider two possible explanations for the absence of results. The first one concerns the adequacy of the MRT test in measuring the spectrum of the spatial abilities. Although the test is widely used to measure spatial skills, it might be not sensitive to some aspects of the spatial ability that intervene in switching between the physical and digital worlds. This explanation would support the hypothesis of Dünser et al. (Dünser et al., 2006), who tried to estimate the trainability of spatial skills through AR systems. According to the authors, the MRT and other standard tests would be limited in measuring the changes of spatial abilities, hence the necessity of developing more accurate metrics.
Our second interpretation is based on the distinction between spatial visualization and spatial orientation made by Strong and Smith (Strong and Smith, 2001). Similar to the concept of spatial awareness proposed by Veas et al. (Veas et al., 2010), spatial orientation is defined as "The comprehension of the arrangement of elements within a visual stimulus pattern and the aptitude to remain unconfused by the changing orientation in which a spatial configuration may be presented". Switching towards the physical substratum of the augmentation seems to be related to spatial orientation rather than spatial ability, as shown by the temporal proximity between moving the tablet in a different position and looking at the physical structure. Our statistical models indicated that the probability of shifting the gaze increases when the residence time decreases and when the speed increases, confirming the hypothesis $\mathbf{H}_{Spatial-Awareness}$. Slow transitions are less likely to trigger any shift, which would explain why the number of transitions did not increase with the travelled space, since the navigation was mostly smooth around the structures. As previous studies have shown, although the magic-lens displays both the physical surrounding and the virtual content, the user should be spatially aware in the physical space as well as in the digital one, where s/he acquires the point of view of the camera. In our experiment, **the physical structures provided a spatial anchor to link and align the physical and the digital spaces**. However, such alignment was likely to be performed bypassing the screen when the user changed largely his/her position. During the final interviews, six participants explicitly reported that they quickly looked at the structure in order to decide the successive points of view.

Holding the tablet with hands rather than having it on a stable support did not result in an increment of the visual references at the physical models as we would have expected according to hypothesis $\mathbf{H}_{AR-Faults}$. The absence of significant difference might be due to the fact that the participants rarely used the freezing functionality in TiH condition but expressed a general positive feedback regarding the AR experience. Although we could have introduced more perturbations to increase the difference between the two conditions, our implementation was based on off-the-shelf AR technology. Hence, having more flaws than the ones present in nowadays AR tools would have weakened the validity of our comparison. Probably, had the experiment been longer, participants in TiH condition would have reached a higher level of fatigue and would have performed more shifts towards the physical structures. We conclude that common AR flaws do not affect significantly the shift of gaze.

Two differences emerged in the two experimental conditions: (1) although the areas navigated by the participants in both conditions were not significantly different, ToS participants moved less than those in TiH condition, preferring to keep the same position for longer periods; (2) the average duration of the intervals spent to look at the physical structure was indeed longer for ToS participants. In ToS condition, the stiffness of the support has limited, to some extent, the navigation around the structures. Even though the tablet could reach the same locations in both ToS and TiH conditions, ToS participants adopted positions from which the tablet view included most of the structure rather than being at close-range. Hence, looking directly at the structure became a way to memorize the model at different scales or from different angles, in order to use this mental representation afterwards when working with the tablet. Considering that mental processes involving the memorization of a scene require longer fixation periods than other processes (Henderson, 2003), the ToS condition was leveraging more on mental representation and the spatial visualization of the structure compared to TiH condition. The fact that such difference did not result in the variation of visual switches between the conditions gives support to our hypothesis that spatial skills do not affect the number of shifts towards the physical layer. There might have been an interaction effect between experimental condition and spatial abilities on the process variables characterizing the shifts, but the statistical power of our study was probably not sufficient to show it.

The number of shifts toward the physical structure did not differ among the four trials, however the Roof and Vault structures received more fixations than the Gazebo and Howe structures. This result reflected the difficulty of the task, which appeared to depend on the asymmetry of the structure rather than on whether the structure was two-dimensional or three-dimensional. Symmetry allows to isolate a part of the structure, to find a solution for that small section and finally to propagate the results to the whole structure. The participants converged on the fact that both the Gazebo structure and the Howe structure could have been reduced respectively to the analysis of a single slice and of the left-side. Since the Roof and Vault structures lack symmetry they required a bigger effort to extract the layouts, to apply the forces and to solve the compression-tension task for the different sub-parts of the models. What is the reason why the number of shifts did not increase proportionally to the difficulty of the task? This is probably due to the inherent attention switch cost. Gutpa (Gupta et al., 2004) found that shifting between the physical and digital stimuli induces eye fatigue. The author investigated the strain caused by switching between real-world context and digital context. In the study setup, the participants were asked to match letters from a text displayed on a screen (physical layer) and a text displayed through head-mounted display (digital layer). The task required the participants to switch between the two sources while the text was displayed at different distances (near 0.7mt, medium 2mt, far 6mt). The results revealed that frequent gaze shifts caused eye fatigue at any distance. Re-orienting visual attention between objects is a time-consuming process (Iani et al., 2001; Brown and Denney, 2007). The average reaction time necessary to shift the gaze between objects is typically longer than the one require to focus on different parts of the same objects. This is due to the fact that a person has to disengage his/her attention from a cued target. In our experiment, the perceived gains offered by shifting back and forth between the structure and the augmentation did not offset its cost. The task difficulty did not lower the cognitive load of shifting the gaze. Instead, the moments of visual attention on the structures got characterized by an indicator of higher cognitive effort, as if the user tried to process the most from these moments and, at the same time, to minimize the need for new transitions.

7.6 Conclusions

This work represents a contribution to the AR field with regards to the role of the physical layer, not only as a background for magic-lens systems. The main result is that looking directly at the physical object seems to sustain the spatial orientation of the user in the physical space when changing locations. Spatial abilities have neither significant effect on the number of shift nor on the gaze behaviour while looking at the target of the augmentation. Similarly, we did not observe any effect due to AR issues such as instability of the augmentation or depth ambiguities. During the shifts, the increment of the task difficulty and the lower controllability of the tablet position changed the gaze property in a way that clearly reflected the higher mental effort of the users. Surprisingly, the two variations did not result in an increment of shifts.
For what concerned StaticAR, this was the first experiment employing it. It provided us with the participants' feedback about the usability of the tool but also with a clearer of the role of the physical structures. Removing the structure while keeping only the hexagonal grid would result in higher difficulty of visualizing its geometry and in a lack of spatial references. Nevertheless, the difference of visual shifts between the four structures revealed that the extent to which the physical model is shaped after the digital one could be designed in function of the structure complexity. Complex structures offers peculiar structural behaviours but require elaborate physical models too. In case of simple and common structures, modelling only the critical parts should be sufficient since the scaffolding provided by the physical model becomes less necessary. Moreover, an advantage of the partial modelling is that one concrete representation can serve to multiple case-studies, fostering the transfer of statics knowledge among different scenarios. We believe that these observations could better inform teachers and apprentices in the selection of the relevant artefacts from the Erfahrraum.

Given the exploratory nature of our study, our findings should be subject of further studies.

Navigation and changes of position should be controlled, for example designing a study in which these variable are the independent ones. Moreover, it should be clarified whether only the target object of the augmentation provided support to the spatial awareness or any other landmark in the physical surroundings. Other researches might consider to repeat the experiment by employing a wider and more sensible range of tests for assessing spatial abilities and might extend the duration of the task to verify if physical fatigue could lead to more and longer shifts.

8 Study IV: Evaluating a Visual Representation of Forces in a Collaborative Task

8.1 Introduction

The purpose of our last study was to describe how apprentices' reasoning is affected by the pictorial representations of the forces used in StaticAR. As previously described in chapter 6, the augmentation of the axial force acting in a beam is made of two components: the arrows at the extreme joints and the spring in the middle of the beam. The spring conveys the effect of the force on the beam, which could get either compressed or elongated. The arrows show the way the beam reacts to the stress by respectively pushing or pulling the extreme joints. Both the representations have strengths and weaknesses. Accepting a spring as a metaphor for timber is straightforward and the usage of such analogy is recurrent in the carpentry teaching. However, from our experience described in chapter 5, the sole representation through the spring might lead learners to overlook how the elements of a structural system interact with each other in order to be in equilibrium. Moreover, the concept of *springiness* (DiSessa, 1983), which summarizes the link deformation $\implies$ reaction force, could be not yet developed in some students, who might lack a physical intuition of how springs work (Lattery, 2005). Hence, we introduced the arrows that provide a cue about the composition of the forces at the joints. The arrows create the free body diagrams of each joint which includes the magnitudes of the forces too [1]. The arrows representation is undoubtedly less immediate and less natural to understand than the springs' one, especially because it relies on the notion of vectors. Research in physics education has shown that such notion could be challenging for novice students (Nguyen and Meltzer, 2003; Nathan, 2012). Furthermore, prompting students to use the arrows as representation to depict forces could prevent them from relying on intuitive methods for solving physics problems, increasing the chances of giving wrong solutions to the exercises (Meltzer, 2005; Heckler, 2010). In order to progressively introduce the formalism of vectors to students and to help them mastering it to represent forces acting between bodies, several authors have proposed alternative visual-representation tools that emphasize forces as a property of the interaction between entities (de Dios Jiménez-Valladares and Perales-Palacios, 2001; Hinrichs, 2005; Savinainen et al., 2013). Following these works, we hypothesized that the

[1] The arrows are scaled according to the magnitude of the force.

combination of springs and arrows should make the action/reaction relationship between the beams on the joints explicit.

For this study we used the compression-tension task again. However, differently from the studies previously described, the participants solved the exercises by collaborating. Exploiting social interaction to foster a deeper understanding of basic physics subjects (e.g. motion and forces) has given positive outcomes, for example, in case of teacher-led peer discussion (Savinainen et al., 2005), of peer instructions with structured inquiry (Suppapittayaporn et al., 2010) or of computer-mediated collaborative problem-solving sessions (Soong and Mercer, 2011).
In our study, the participants formed pairs in which one apprentice received a tablet running StaticAR with only the springs representation available; the other received another tablet displaying only the arrows representation. After completing the task individually, they had to collaborate to provide the final answers to the exercises. The rationale for this script of the experiment flow could be found in the design principle "Split Where Interaction Should Happen" (SWISH) (Dillenbourg and Hong, 2008). The idea of the SWISH is to let the participants' understanding emerge by introducing some differences that force them to discuss, to negotiate and to argue. In our case the difference was induced by the adoption of the two different representations which do not appear equivalent at first sight. However, the apparent discrepancy should dissolve as the participants collaborate, resulting in a synthesis of the two representations. Furthermore, in terms of data collection, this type of approach would elicit the participants' verbalization of their reasoning in a natural way, overcoming the artificiality of the think-aloud protocol noticed in Chapter 5.

The research objectives of this experiment were:

- to check if any learning gain resulted from the proposed activity (pre- and post-test comparison);
- to look at the performance in the experimental task in order to get insights about the impact of the two representations on the individual phase and about the effect on the discussion phase.
- to identify what worked or did not work in the activity with StaticAR in order to extract directions for future improvements.

8.2 Experimental Setup

8.2.1 Participants

This study was run at the Centre d'Enseignement Professionnel de Morges (CEPM) during the spring semester 2017 and it involved 22 carpentry apprentices, all males, belonging to two classes. The students were in their third year of training, hence the bases of statics had already

been presented by the teachers. When the study took place, the students were completing the module of the school curriculum concerning the behavior of supported beams, after which they would have started an introduction to more complex structures.
The apprentices were invited in pairs to take part to the experiment during the school time. The participation was spontaneous and the formation of the pairs was left to the students. Except for one group, the pairs were formed by apprentices that seated next to each other, hence we could assume some degree of acquaintanceship between them that would not inhibit their discussions.

8.2.2 Procedure and Materials

Table 8.1 – Phases of the experiment.

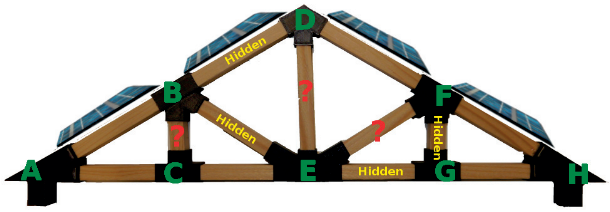
Step	Description		
1.	Statics Knowledge Pre-Test		
2.	Howe	Solving	Individual phase
3.	Gazebo	Solving	
4.	Roof	Solving	
5.	Vault	Solving	
6.	Howe	Discussing Verifying	Collaborative phase
7.	Gazebo	Discussing Verifying	
8.	Roof	Discussing Verifying	
9.	Vault	Discussing Verifying	
10.	Statics Knowledge Post-Test		

Before and after the experimental task, apprentices completed individually the statics knowledge test developed in Chapter 5 (Appendix B) in order to assess any change in their statics thinking skills. The test had a time limit of 9 minutes and it contained 21 questions (3 questions x 7 structures). The compression-tension task remained unchanged: for each structure subject to external loads, the participants had to say the axial forces acting in three beams (compression, tension or zero-force). The experiment included the analysis of the four structures used in the previous study but with different load configurations (Figure 8.1). The participants used the latest version of StaticAR as described in Chapter 6 running on an Nvidia Shield tablet with 8-inch display.
The protocol of the experiment is shown in Table 8.1. During the individual phase, each participant solved the four exercises with the support of the assigned representation (Figure 8.2). The three beams for which the students had to provide an answer were highlighted in yellow on the tablet. The augmentation showed the forces acting in some elements of the

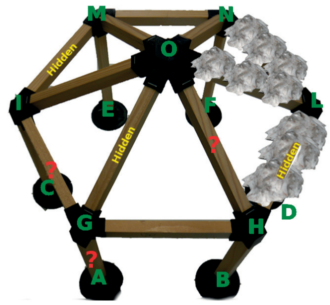
structures while hiding those acting in the question beams and in some beams that would make the answers trivial. Besides this information, the interface did not provide any feedback nor allowed accessing any function of StaticAR. The answers were marked on the sheets attached to the tablets (Figure 8.3). Only when both participants had completed an exercise, they could move to the next one.
During the collaborative phase, the two apprentices were asked to sit next to each other and, for each structure, they had to compare their solutions and discuss their final shared answers. Each participant kept the tablet with the representation used in the individual phase, but they were invited to share the devices and to make use of both visualizations. Only when an agreement was reached on the three answers of a structure, the participants could verify the correctness of their solutions which were shown on both tablets. For the verification phase the tablets provided the combination of the springs and the arrows. When needed, the participants could also use the additional functions offered by the application[2] (e.g. deformations, removing beams, changing supports, etc..). No time limit was set either for the individual phase or for the collaborative phase.

Regarding the data collection, the whole sessions were video recorded in order to analyze the dialogues between the apprentices. Although it would have been interesting to assess the quality of the collaboration by employing eye-tracking measures (Jermann et al., 2012; Sharma et al., 2013; Schneider et al., 2013a), the setup of a dual mobile eye-tracking system was prohibitive due to technical difficulties (Clark and Gergle, 2011, review).

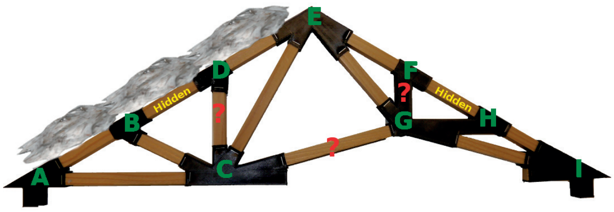
[2]The experimenters offered support to the apprentices to access such functions.



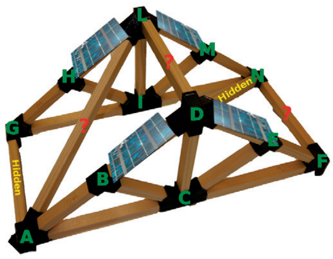
(a) Howe Truss



(b) Gazebo Structure



(c) Vault Truss



(d) Roof Structure

Figure 8.1 – The four structures used in the compression-tension task.

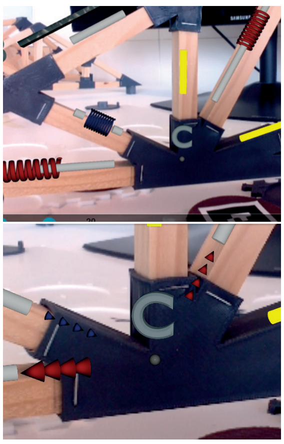


Figure 8.2 – Representation of forces by springs or arrows.

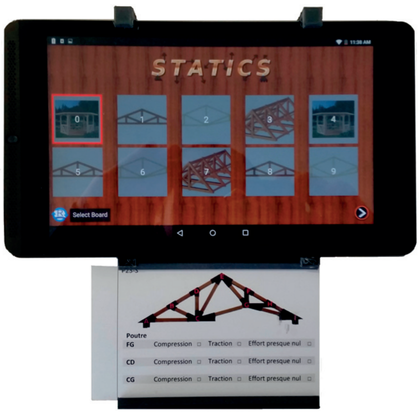


Figure 8.3 – The answer sheet attached to the tablet.

8.3 Statistical Analysis and Findings

For the statistical analysis we used the software R v3.2(R2016) along with the package 'lme4' (Bates et al., 2015) to fit generalized linear mixed models. As usual, the interpretation of the results is given in the discussion section.

Pre- Post-test Learning Gain The median score in both pre- and post-test was 13 out of 21 (IQR$_{pre}$: 2.75 and IQR$_{post}$: 3). There was no significant difference between the pre-test and post-test scores in the pairwise comparison (V=99.5, p=0.87, Figure 8.4) and the average learning gain[3] was 1% (SD: 16%). The type of representation, either arrows or springs, did not affect the average relative learning gain significantly (W=43.5, p=0.28) . Similarly, when analysing the correctness of the single answers in each question of the post-test, we could not appreciate any sensible variation due to the representation (Figure 8.5). It did not have a main effect on the correctness of the questions ($\chi^2(1) = 0.12$, p=0.73) and there was no significant interaction effect between the representations and the questions ($\chi^2(21) = 15.76$, p=0.78). The results might be related to the short duration of the experiment, which was not sufficient to lead to an improvement in the task, and also to the fact that the post-test took place after the collaboration phase in which participants had access to both visualizations. As observed in the previous study of Chapter 5, the percentage of zero-force members correctly identified remained significantly lower than the percentage of the compression and tension forces (F[2,129]=38.09, p<0.001).

Performance in the Experimental Task As regards the performances during the individual and collaborative phases of the experiment, Figure 8.6 shows the number of participants (or pairs) who gave a correct answer for each question. What results clearly from the graph is that there was no advantage of using one representation over the other in the individual phase, nor the collaboration phase brought higher scores. We fitted a logistic model for the correctness of the questions including the question, the phase and interaction between them. However, both the main effect of phase and the effect of the interaction were found to be not significant ($\chi^2(2) = 0.49$, p=0.783, $\chi^2(24) = 20.14$, p=0.688). Furthermore, no significant correlation was found between the pre-test score and the intervention score of the individual phase ($r_s = -0.07$, p=0.75).

As we previously said, the pairs were formed spontaneously by the participants. When the answers given to a question during the individual phase were the same, the apprentices did not discuss their solutions in two-thirds of the cases ($\chi^2(1) = 14.40$, p=0.0001). In such cases, almost 64% of the time both answers were correct. As a consequence, the probability

[3]

$$RLG = \begin{cases} \frac{score_{post-test} - score_{pre-test}}{21 - score_{pre-test}} & \text{if } score_{post-test} - score_{pre-test} \geq 0 \\ \frac{score_{post-test} - score_{pre-test}}{score_{pre-test}} & \text{if } score_{post-test} - score_{pre-test} < 0 \end{cases}$$

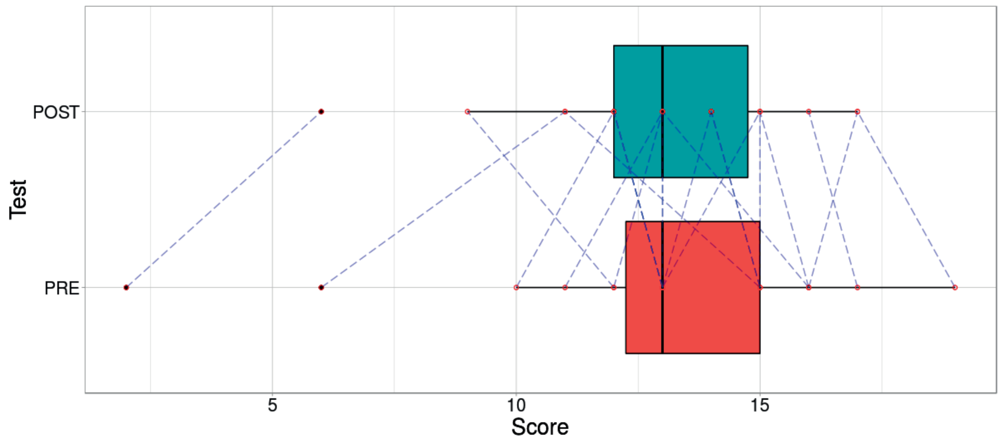


Figure 8.4 – Scores in pre-test and post-test. The single dash line connects the scores of a single participant.

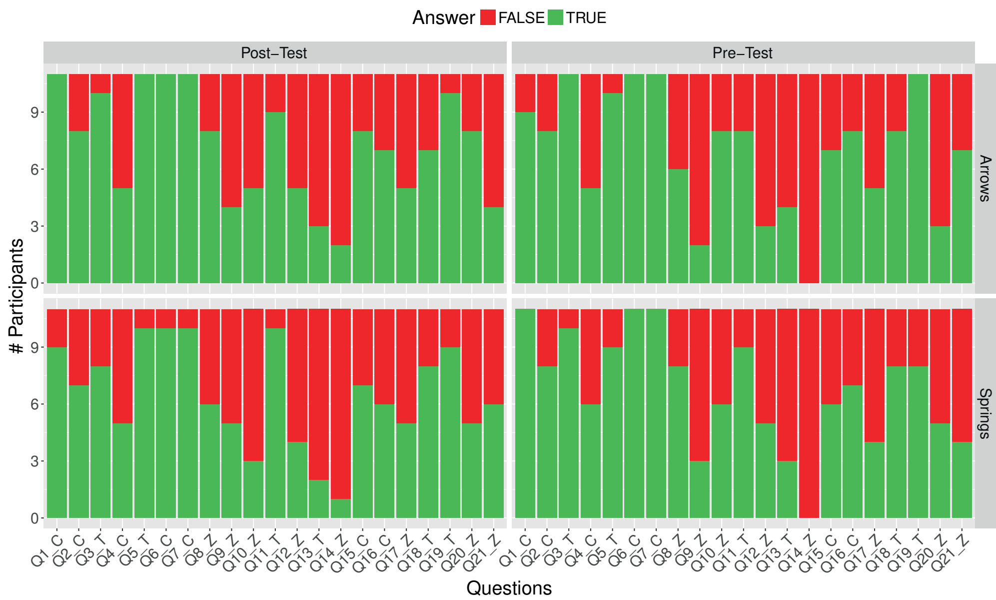


Figure 8.5 – Distribution of correct answers in the pre-test and post-test.

of giving a correct answer in the collaborative phase was higher when the students agreed on it than when the students had to converge to a shared solution (GLMM, $\beta = -0.95$, Std. Err=0.42, $\chi^2(1) = 5.18$, p=0.02, the relation worked vice-versa too $\chi^2(1) = 4.65$, p=0.03). In case of disagreement, we could not find evidence indicating that the peer adopting one representation was dominating the choice of the final answers (Figure 8.7). In the figure, the only exceptions seem to be groups 7 and 9, even though from their dialogues we did not observe differences compared to the other groups. The discussions of group 7, in which the participant with the springs representation seemed to impose his solutions, were characterized by frequent contribution from both apprentices. Table 8.2 describes the correctness of the answers given in the collaborative phase in relation to the correctness of the answers given

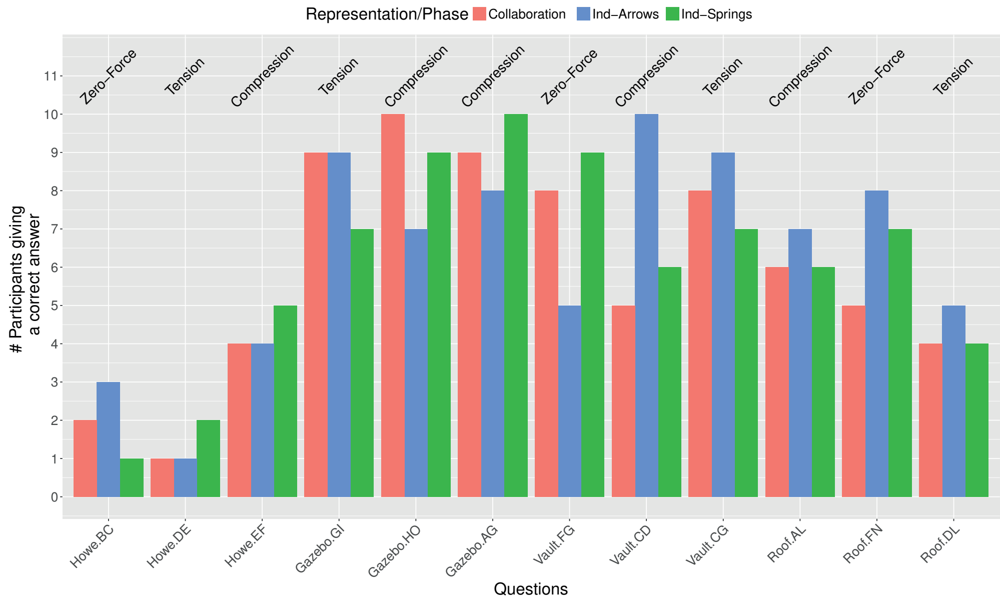


Figure 8.6 – Distribution of correct answers in the compression-tension task.

Table 8.2 – Correctness of the answers given in collaborative phase in relation to correctness of the answers given in the individual phase.

	Answers Collaboration Phase	
Answers Individual Phase	**Correct**	**Incorrect**
(TT) Both Correct	42	6
(AT) Arrows Correct	15	10
(ST) Springs Correct	11	17
(FF) No correct	3	28

in the individual phase. The first and last rows trivially describe that when the answer given by the two students in the individual phase was correct/incorrect, then their answer in the collaborative phase was likely to be respectively correct or incorrect too. The second and third rows describe the case when the apprentices disagreed but one of them gave a correct answer in the individual phase. It seemed that the apprentices with the arrows representation were more successful in convincing their partners than the apprentices who adopted the springs representation. We built a logistic model of the columns of table including the rows as levels for the main effect ($intercept_{FF} = -2.23$, Std. Err=0.6, p<.001, $\beta_{TT} = 4.17$, Std. Err=0.74, p<0.001, $\beta_{AT} = 2.63$, Std. Err=0.73, p<0.001, $\beta_{ST} = 1.79$, Std. Err=0.72, p=0.01, $\chi^2(3) = 55.17$, p<0.001). However, the pairwise comparison of the levels AT ans ST resulted in a lack of statistically significant difference (p=0.44). At this point, we started investigating the factors that contributed in the success of the discussion when the apprentices did not agree on their answers. The number of turns taken by each apprentice in the discussions did not have a significant effect on the correctness of the final questions, meaning that the participation did not play a crucial role ($\chi^2(1) = 0.19$, p=0.66). Then, we hypothesized a relation between

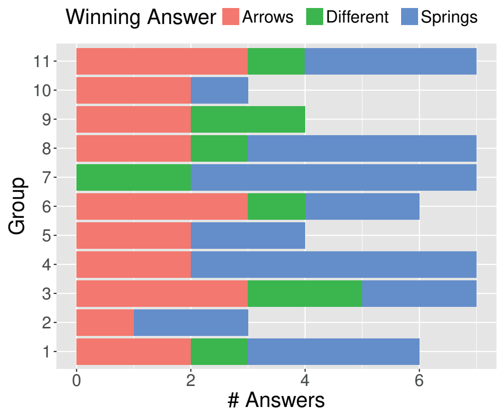


Figure 8.7 – Dominance in the collaboration phase.

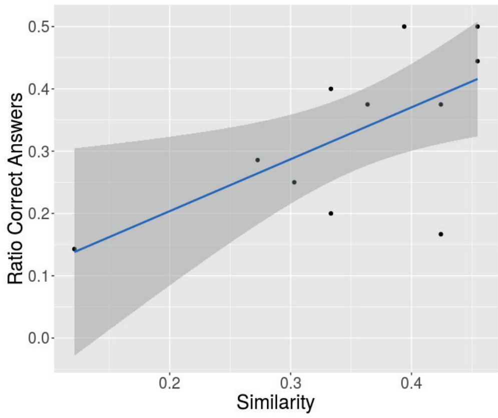


Figure 8.8 – Relation between similarity of the pair based on the pre-test and the ratio of correct answers given to the questions participants did not agree on.

the score achieved in the collaborative phase and the similarity of the students based on the pre-test, meant as a measure of homogeneity of the group. The similarity in a group was defined as the number of equal answers given by two participants in the pre-test normalized by the number of questions. The formula for the similarity between two students i and j was $1 - \frac{\sum_{k=1}^{21} d_{ij}^k}{21}$ where $d_{ij}^k = 0$ if the answers given by the students were the same, otherwise $d_{ij}^k = 1$. Obviously, if two students were good in answering the questions then their similarity would be high, while the inverse implication does not hold. Hence, such formula should be decomposed in two parts: similarity on answers to pre-test questions that were either correct (1) or incorrect (2). The similarity did not improve our logistic model ($\chi^2(2) = 2.81$, p=0.25). We built a dataset in which we counted the correct answers given by each group and fitted a model including the two parts of the similarity as main effects and the number of questions the apprentices did not agree on as offset. Both parts (1) and (2) were found to have a main effect on the score ($\beta_1 = 2.79$, Std. Err=1.09, p=0.003, $\beta_2 = 4.44$, Std. Err=2.03, p=0.06 $\chi^2(2) = 1.87$, p=0.01). The main effect of the similarity in the pre-test was unexpected, especially in the light of the absence of any correlation between the pre-test score and the score during the individual phase. A graphical representation of the result which reports on the x-axis the similarity and on the y-axis the ratio between correct answers and the offset is given in Figure 8.8.

Table 8.3 shows the usage of the tablets and of the structures during the discussion phase. The participants shared the tablets with their partners in almost 50% of the cases when giving explanation. This was less common when working on the Vault structure because, due to the difficulty of the structure, the apprentices were visibly less confident about their explanations and struggled to find support for their reasoning in the augmented visualizations. The majority of the explanations were given by referring to the physical structures and were complemented by technical terms or by body gestures.

Table 8.3 – Characteristics of the collaboration phase.

	Sharing Tablet		Use of the structure	
	Yes	No	Yes	No
Howe	5	6	8	3
Gazebo	6	5	5	6
Roof	6	5	9	2
Vault	2	9	7	4

Carpentry terms[4] appeared in 12 explanations and in 9 of them the correct recognition of the function of a beam lead the students to the correct identification of the axial force acting in it. As said above, explanations supported by body gestures were largely used during the discussions. An interesting example is given in Figure 8.9 which reports the dialogue between two apprentices who were analysing the beam DL of the Roof structure. In the individual phase, the student who was using the arrows representation thought that the beam was compressed. However, he changed his mind during the collaborative phase and realized that the beam was in tension. His explanation was definitely "physical". He grabbed the two bottom rolling joints and explained that they should move outwards due to the loads (Figure 8.9a). His explanation continued by saying that such displacement causes the two faces of the structure to move apart. Thus, in order to compensate for the displacement the beam DL should be in tension. The first time the participant said that the beam was pulling, his hands were moving apart (Figure 8.9b). The subject of its sentence was the beam, but the gesture was representing the beam as the object of a pulling force. The verbalization was ambiguous since both the beam and the two joints were pulling something. When the apprentice looked at his hands he realized the discrepancy between what he said and what he was showing. His gesture was representing the effect of the force on the beam. Thus, he changed the gesture in order to represent the action of the beam on the joints and claimed that the beam was working in tension (Figure 8.9c). The last gesture was coherent when the arrows representation. The apprentice produced a mismatch between speech and gesture, which respectively referred to the arrows representation (which was the one assigned to the participant) and the spring one.

The above example was not an isolated episode and, indeed, the analysis of other dialogues revealed the development of conceptual understanding among some apprentices.
The dialogue in Table 8.4 belonged to a group discussing the force acting in the beam BC of the Howe structure. In the individual phase both apprentices marked the beam as in compression but during the collaboration phase they questioned their choice. Both apprentices

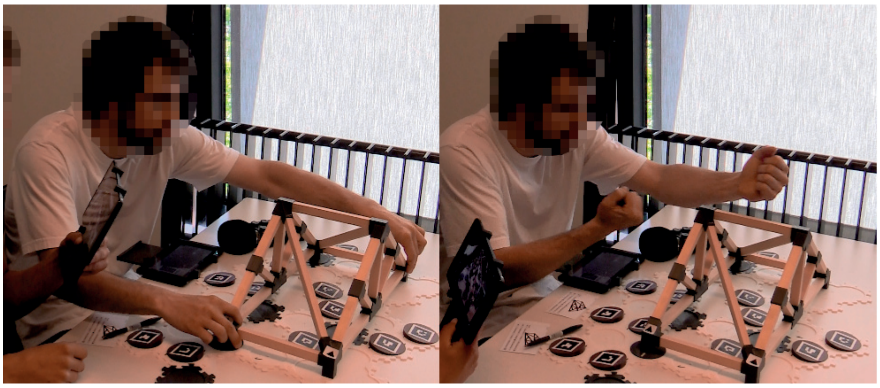
[4] The four terms found in the dialogues were:

Sablière : horizontal beam used to support the floors or the different pieces of vertical or oblique wood truss. Used for AG and FN in Roof;

Contrefiche : oblique element found in trusses. Used for BE and EF in Howe;

Contreventement : an element that stabilizes the structure against wind forces. Used for AL and DN in Roof;

Poteaux : A post that is a vertical element similar to a column. Used for AG in Gazebo.



(a) **Arrow Participant**: *Look, it moves like this [outwards]. It opens the two parts.* He noticed that the bottom supports could slide apart.

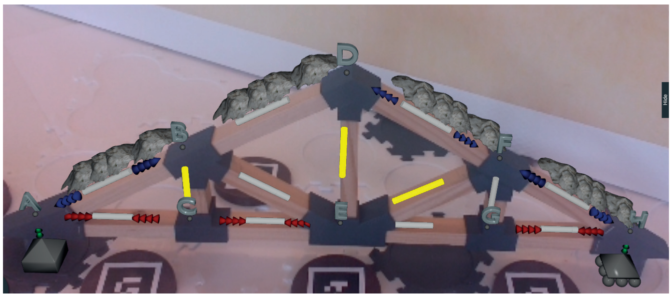
(b) **Arrow Participant**: *So it pulls. It works this way....* He looked at his hands and realized that he was representing the effect of the force on the beam instead of the way the beam was working.

(c) **Arrow Participant**: *Well, it pulls them together.* He changed the gesture. Both participants finally agreed that the beam was in tension.

Figure 8.9 – Body gestures complementing the explanations.

were looking at the tablet showing the visualization with the arrows. The arrows participant described the known forces and, most importantly, the fact that the load was acting vertically on the structure. At this point the other apprentice built his first explanation noticing that in the triangle ABE most of the load should go in AB and BE. Although this explanation did not account for BC being a zero-force member, it was correct to say that BE was in compression. What convinced the two students was that AE could be pulled only horizontally, hence it could not handle any hypothetical strong vertical load deriving from the compression of BC. Using more formal terms, the apprentices concluded that the axial forces developed in AC and CE could not have a vertical component, hence they could not counterbalance any force along BC.

Table 8.4 – Discussion on the beam BC of the Howe structure. In the individual phase both apprentices marked BC as compressed.



Arrows Participant:	So this one (AB) is in compression and the bottom part is in tension (AC and CE). The load is vertical.
Springs Participant:	Well, BE should push B and no load goes on BC.
Arrows Participant:	So you say zero force. Why?
Springs Participant:	The load pushes from the top. A small part is taken by BC, but most of the charge is taken by the big triangle (ABE).
Arrows Participant:	So the forces are taken on the *contrefiche* (BE).
Springs Participant:	Yes, the force pushes on AB, CE is stretched along this way (horizontal), so I don't think BC is compressed.

Force Representation Regarding the representation of the forces, the one using the arrows puzzled some apprentices who had to look at the legend or to ask to their colleagues in order to make sense of the meaning of such representation. An extreme example is reported in Table 8.5. In this case, the students are discussing about the nature of the force in the beam DL in the Roof structure. The apprentice assigned to the springs representation asserted that the beam was in compression and that it was pulling the nodes. At this point the apprentice who adopted the arrows representation recognized an inconsistency. In his colleague's description, the beam itself was causing the compression by pulling its extreme joints. It is hard to tell if such mistake derived from a wrong understanding of the behavior of springs, that might have been interpreted as actuators, or if it was just a problem of verbalization. The other apprentice (arrows representation) did not grasp the meaning of the arrows well enough to bring his partner on the right track. His spread gesture clearly conveyed an idea of elongation while he was saying that the beam was in compression. The two apprentices did not manage to link coherently the arrows representation with the springs representation and ended up with the following doubt: what is in compression? Is it the beam? Or is it the node that gets compressed by the beam? In the end, they asked a clarification to the experimenters.

Table 8.5 – Example of wrong understanding of the representations of the axial forces.

Arrows Participant:	Why do you say compression?
Springs Participant:	The beam pulls the node (Joint L).
Arrows Participant:	But you just said compression.
Springs Participant:	Yes, because it pulls.
Arrows Participant:	But compression is like this (he makes a spread gesture along the beam).
Springs Participant:	No, that's tension. Compression is like this (he makes a pinch gesture along the beam). You compress the fibres.
Arrows Participant:	No, you compress the node. Right?
Springs Participant:	I don't know.

Load Representation An aspect that should be improved in StaticAR is the representation of the external loads. Currently, the loads are displayed as common objects (solar panels, snow, etc.) and the loading forces are directed towards the ground. However, the direction of the forces is not explicitly represented and we observed several apprentices assuming that the forces were acting perpendicularly to the beams. The orientation of the mesh could be misleading for some students who require a visual aid to disentangle the direction of the forces from the orientation of the digital meshes (Figure 8.10).

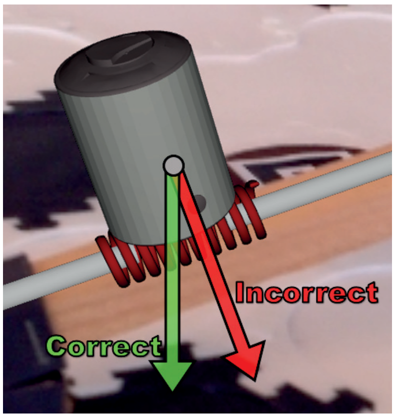


Figure 8.10 – Direction of the forces due to external loads. Some apprentices related the direction of the force to the orientation of the digital mesh.

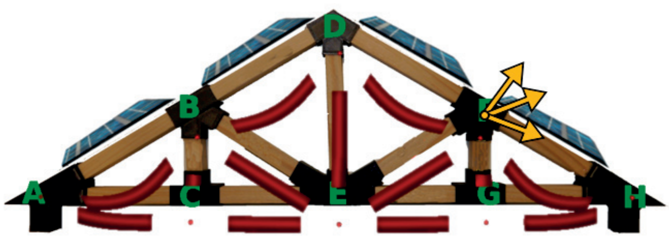


Figure 8.11 – Displacement of the joints in the structure Howe (red). Six apprentices imagined that the joint F would slide on the right following the joint H (orange arrows).

Mistakes in Considering the Displacements A common strategy for solving the compression-tension task was to consider how the structures would deform and and how the joints would be displaced. Although this could be a viable strategy, we noticed two recurrent mistakes that derived from wrong assumptions when imaging the deformation of the structures.

The first type of mistake included considering additional constraints at the joints. When analysing the force acting in the member BC of the Howe structure, an apprentice explained that "the beam BC is in compression because the point C does not move and there is the load that pressed from above". However, since the point C was not constrained the answer was wrong[5]. Two apprentices from two different groups made similar assumptions when analysing the Gazebo structure. In these cases, the joint O was believed to be fixed, thus the connected beams were said to be in tension due to the external loads. The mistake was corrected by the other team members who could use the physical model to show that the joint was free.

The second type of mistake was found in the reasoning on the Howe and Vault structures. In both structures, a rolling support was placed at the bottom right joints. It was clear to the apprentices that the load configurations caused a displacement of these joints towards the right. However, such movement induced six students to think that the neighbor joints too would move sideways under the effect of a force directed in the horizontal direction. According to this view, for example, the beam EF in the Howe structure was in tension because the joint F followed the joint H: "The point J is movable and it goes this was [on the right]. Thus the beam EF gets twisted and slightly goes in tension."(Figure 8.11, yellow arrows).

Attempts to Use the Arrows in the Post-test. Four apprentices attempted to use the arrows symbolism to solve part of the post-test. Figures 8.12a, 8.12b and 8.12c show the representation used to solve the first question of the test. Even though this question was extremely simple, the beam AC was incorrectly identified as in tension in the three examples, and in one of them the same mistake was done for AB. Surprisingly, none of the participants made such mistakes in the pre-test, hence they were caused by some misuse in the representation of the forces through the arrows. In Figure 8.12a, the apprentice, who was assigned to the springs representation, correctly identified AB as compressed. However, he marked AC as in tension probably because he thought that the sliding joint C would pull AC. As previously said, we observed that some apprentices mapped the displacement of a sliding joint into a sort of pulling force that elongates the connected beams. The second example (Figure 8.12b) is from a student who used the tablet showing the arrows representation. The direction of the two vectors could be seen as a correct free-body diagram for the beam AC. However, the interpretation given by the students followed the semantic used in StaticAR, which uses the arrows to represent the forces exerted by the beam on the joints. A similar mistake is visible in Figure 8.12d, in which the apprentice drew the arrows pointing inward in BC to indicate compression, but then he used an arrow pointing outward for the compression of AD. As a consequence, he might have interpreted the arrow at B as some force pulling AB which became in tension (the answer was correct in the pre-test). Figure 8.12c shows a different

[5] His answer would have been correctly if there was a support at the joint.

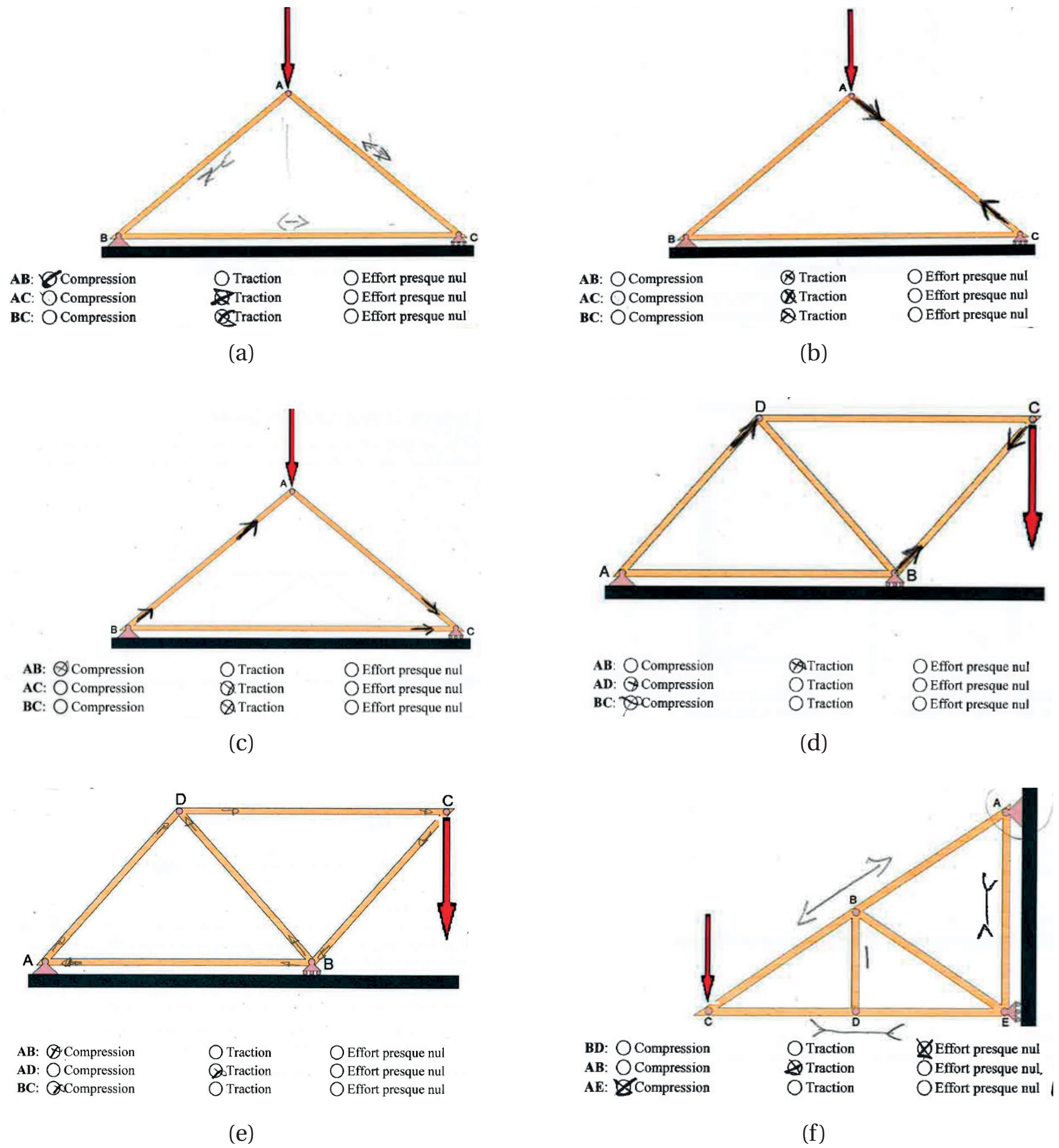


Figure 8.12 – Misuse of the arrow notation in the post-test.

usage of the arrows as a way to represent some sort of “flow” of the forces. The arrows at the extreme joints of the beam AB were drawn in the same direction. The same student used this approach to solve the second question too (Figure 8.12e). Although his answers were correct, he clearly did not know how to handle the supports. In the drawing, the supports seem to not change the “flow”, revealing that the apprentices did not have a clear understanding of how the constraints worked. In Figure 8.12f, another student used the arrows pointing outward to denote tension and the ones pointing inward for compression. The graph was almost correct and he managed to identify all the members correctly except for AE, which was a zero-force member. The mistake might be due to recognition of the triangular pattern ACE. Apprentices learn that a triangle is a stable geometry and that usually there is one member in tension and two others in compression (or vice-versa). However, often students do not pay attention to the location of the supports and their nature, thus they make mistakes like the one just described.

Multiple Correspondence Analysis and Clustering Lastly, we performed a Multiple Correspondence Analysis (MCA) on the pre-test, intervention and post-test answers, followed by a hierarchical clustering analysis. The aim was to identify groups of apprentices whose answers can describe recurrent difficulties. The purpose of MCA was to extract principle components that could summarize the students' answers. Since the answers were categorical variables having three levels (compression, tension, zero-force), the MCA featured as a preliminary step to transform such variables into continuous ones, which successively formed the input to the hierarchical clustering (Ward's method) (Husson et al., 2017, Chapter 4). The methods employed in our analysis belonged to the R package *FactoMineR* (Lê et al., 2008). The number of clusters was chosen on the basis of the heuristic rule implemented in the package. This criterion suggests to keep the K clusters that minimize $\frac{\delta(K)}{\delta(K-1)}$, where $\delta(K)$ is the increment of the between-clusters variance when passing from K-1 to K clusters (Husson et al., 2010).
The clustering of the answers given in the compression-tension task resulted in too many and hardly interpretable clusters. Hence, we reported the results only for the pre-test and post-test questions.

For the pre-test answers the method suggested eight clusters. The answers characterizing the first four clusters are reported in Table 8.6. The other clusters are omitted because they were formed by only one student each. In particular, clusters 7 and 8 were formed by two apprentices who performed poorly during the pre-test and whose answers denoted a serious lack of statics intuition. The first cluster was formed by the apprentices who showed to master well the concept of zero-force member, even though with some mistakes (e.g. Q16 should be in compression). Conversely, the answers characterizing the second cluster suggested that these 4 students did not have such concept clear since the correct answer to Q9, Q10 and Q20 was zero-force but they never chose it. The interpretation of the third cluster should be done with some caution since the only description was that apprentices marked the beams in questions Q12 and Q13 as compressed. When looking at these questions, the impression was that the mistakes rose from a poor understanding of the constraints provided by a rolling support (in particular that such supports prevents vertical translations) that caused an erroneous visualization of the deformations of the structures in question. A similar interpretation might be given for the fourth cluster, especially on the account of the answer "tension" to question Q12.

The eight clusters drastically reduced when analyzing the post-test from which we extracted only four clusters. Four apprentices from cluster 1 moved to cluster 9, whereas 1 apprentice came from cluster 2. The four apprentices from cluster 1 preserved their correct intuition on the answers to Q9 and Q20 being zero-force. However, three of them and the student from the

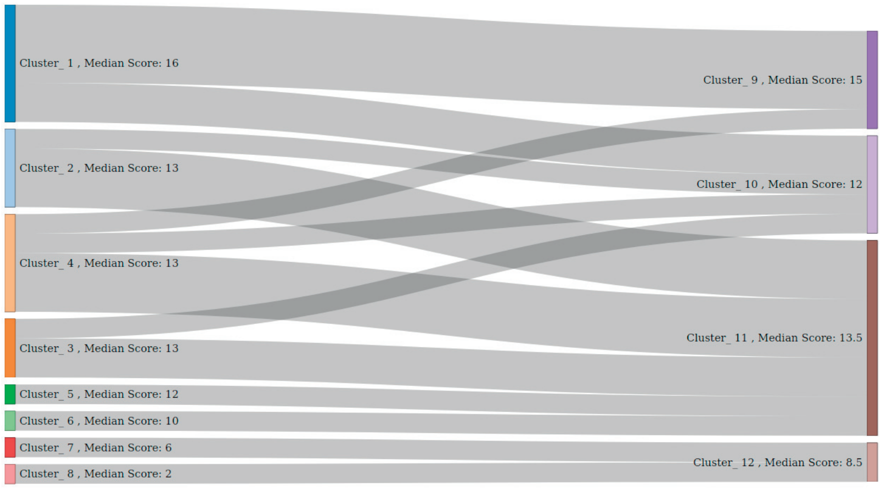


Figure 8.13 – Transitions from the clusters found in the pre-test to the ones found in the post-test.

cluster 2 marked the beam of Q13 as in compression which, as said above, might indicate some difficulty in interpreting the role of the rolling supports. Such difficulty might also explain the presence in the cluster of two students who answered zero-force to question Q2.

The interpretation of cluster 10 was not dissimilar from the one of cluster 9. The three questions Q2, Q9 and Q15 concerned beams that were attached to a sliding support on one side. As previously said, in the collaborative phase we observed that some participants associated the displacement of a rolling support to the presence of a force that stretches the connected beams. Apprentice belonging to this cluster might have fallen in the same mistake. They answered tension to questions for which the beams were either in compression (Q2 and Q15) or zero-members (Q9). Interestingly, when looking at the answers given by these 5 apprentices to the three questions in the pre-test, in the majority of the cases apprentices gave correct answers or, at least, made a plausible mistake [6]. Moreover, two apprentices belonging to this cluster 10 also attempted to use the arrows to solve the post-test.

The last two clusters did not provide interesting insights. Cluster 11, which was the largest one, was mostly described by correct answers except for the case of Q20. For this question participants in cluster 11 chose always “compression” instead of “zero-force”. This cluster absorbed most of the pre-test ones and its median score was higher compared to scores of the initial clusters. Considering only the 10 participants belonging to cluster 11, we found that the median RLG was positive (median: 12, IQR: 19) but the pairwise between pre- and post-test comparison was not significant (V=6, p=0.09). Lastly, cluster 12 contained two of the apprentices who performed poorly in the pre-test but improved in the post-test. Nevertheless, they were the only two participants who answered compression to both Q19 and Q5, which was a very counterintuitive answer.

In conclusion, the exploration through MCA and clustering confirmed the findings from the

[6] Even though the answer to Q9 was zero-force, it could be easily mistaken for compression.

previous paragraphs. We observed a little improvement for apprentices in cluster 11. Regarding the concept of zero-force members, an intuitive understanding of it could blossom even without specific training (cluster 1). However, from the transitions between pre-test and post-test clusters, cluster 1 turned almost unvaried into cluster 9 which included only one apprentice from a different cluster. Moreover, no other post-test cluster was characterized by correct answers to zero-force questions. These results suggested that the understanding of the zero-force concept was not affected by the intervention. The cluster analysis also highlighted the need to tackle misconceptions about the role of the type of supports and their reactions. On these topics, it would be opportune to develop an activity in StaticAR.

Table 8.6 – The first four clusters extracted from the pre-test answers.

	Cluster 1, 6 apprentices		
Answer	Answer/Cluster	Cluster/Answer	v.test
Q17:Zero-Force	100	60	2.98
Q16:Zero-Force	66.66	80	2.59
Q10:Zero-Force	83.33	62.55	2.53
Q12:Zero-Force	83.33	55.55	2.25
Q20:Zero-Force	100	42.85	2.05
Q8:Zero-Force	100	42.85	2.05
Q13:Compression	0	0	-2.05
Q17:Tension	0	0	-2.27
	Cluster 2, 4 apprentices		
Answer	Answer/Cluster	Cluster/Answer	v.test
Q9:Compression	100	44.44	2.38
Q10:Compression	100	40	2.18
Q20:Zero-Force	0	0	-2.59
	Cluster 3, 3 apprentices		
Answer	Answer/Cluster	Cluster/Answer	v.test
Q12:Compression	100	50	2.38
Q13:Compression	100	37.5	2.18
	Cluster 4, 4 apprentices		
Answer	Answer/Cluster	Cluster/Answer	v.test
Q21:Zero-Force	100	45.45	2.37
Q12:Tension	80	57.14	2.29

Answer/Cluster: Percentage of participants of the cluster who gave that answer.
Cluster/Answer: Percentage of participants who gave that answer and also belonged to that cluster.
The v.test sign indicates if the answer is over-represented (positive) or under-represented (negative) in the cluster.

Table 8.7 – The four clusters extracted from the post-test answers.

Answer	Answer/Cluster	Cluster/Answer	v.test
Cluster 9, 5 apprentices			
Q9:Zero-Force	80	80	2.93
Q13:Compression	80	66.66	2.59
Q20:Zero-Force	80	50	2.03
Q2:Zero-Force	40	100	2.02
Q20:Compression	0	0	-2.82
Cluster 10, 5 apprentices			
Answer	Answer/Cluster	Cluster/Answer	v.test
Q15:Tension	100	100	4.11
Q2:Tension	80	100	3.39
Q9:Tension	80	50	2.03
Q2:Compression	20	6.25	-2.59
Q15:Compression	0	0	-2.82
Cluster 11, 10 apprentices			
Answer	Answer/Cluster	Cluster/Answer	v.test
Q20:Compression	100	76.92	3.51
Q16:Compression	100	66.66	2.83
Q2:Compression	100	62.5	2.50
Q13:Tension	60	85.71	2.40
Q16:Zero-Force	0	0	-2.16
Q15:Tension	0	0	-2.16
Q20:Zero-Force	0	0	-3.16
Cluster 12, 2 apprentices			
Answer	Answer/Cluster	Cluster/Answer	v.test
Q19:Compression	100	100	2.85
Q5:Compression	100	100	2.85
Q18:Compression	100	40	2.02
Q19:Tension	0	0	-2.48
Q5:Tension	0	0	-2.48

Answer/Cluster: Percentage of participants of the cluster who gave that answer.
Cluster/Answer: Percentage of participants who gave that answer and also belonged to that cluster.
The v.test sign indicates if the answer is over-represented (positive) or under-represented (negative) in the cluster.

8.4 Discussion

The experiment ran smoothly and no major issue was reported by participants. From their perspective the technology was obviously not novel: it appeared as a regular mobile app, and one student even asked if it was available on the app markets. The apprentices got quickly used to the interface and expressed a general positive appreciation for the tools that it provides.
The teachers' feedback was positive too. They particularly appreciated the fact that the activity was not built only around the tablets but it encompassed the collaboration between students and the interaction with physical models too. Thus, they saw the potential for integrating StaticAR in the current practice because it does not completely revolutionize it.

The first aim of this study was to show whether the activity could lead to any learning gain. It was frustrating to see the lack of significant improvement in the average score between pre- and post-test. The average learning gain was marginally positive, although the standard deviation was quite large (16%). The adoption of either one representation or another did not have an effect on the learning gain. As said above, a possible explanation for the result was that in the collaborative phase the apprentices shared their tablets, hence they had access to both representations.
Whether the apprentices worked with forces represented by arrows or by springs, the average scores in the individual phase of the experimental task were similar. The collaboration phase did not lead to a general improvement of the intervention scores. However, our finding suggested that the success of the collaboration phase could depend on the similarity of the apprentices' prior knowledge. It is well known from collaborative learning and computer-supporter collaborative learning research that there is no golden rule to decide whether a group should be composed by homogeneous learners (e.g. same level of abilities, same culture, etc.) or heterogeneous ones (Dillenbourg and Schneider, 1995). Some authors found that heterogeneous groups explore more the problem space and create more alternative explanations which results in a reacher learning experience (Jermann and Dillenbourg, 2003). Other works have shown that when learners are involved in learning processes on complex topics, such as maths or physics, homogeneous dyads performed better than heterogeneous ones (Fuchs et al., 1998; Gijlers and De Jong, 2005). Our results leaned towards the second case. The number of equal answers given in the pre-test by two participants, whether these answers were correct or incorrect, had a positive significant effect on the score of the collaboration phase, whereas the pre-test score did not have any correlation with the score of the individual phase. It seemed that scoring high in the pre-test did not influence the score in the intervention when working individually. However, working with someone who gave similar answers created a fertile ground for achieving high score in the collaboration phase. Especially when considering that the experiment duration was likely to be insufficient to consolidate new intuitions, pairing students having a large gap between their abilities might not have resulted in the reciprocal scaffolding, but it could have hindered the peer who was in a transitional state. The results seem to suggest that the development of an intuitive understanding of statics requires collaboration between learners who have a homogeneous prior-knowledge.

If the quantitative analysis did not offer many insights about the effects of activity, the qualitative analysis of the dialogues revealed a germ of correct understanding in some of the apprentices' reasoning which were deeply influenced by the two representations.
An example was given by the episode about the mismatch of gestures and speech that we interpreted in the light of the studies of Perry, Church and Goldin-Meadow (Perry et al., 1992). According to the authors, the occurrence of gesture-speech mismatches can be considered a signal of transitional knowledge in a person's acquisition of a new concept. Since the concept has not been consolidated yet, the learner produces alternative procedures that emerge either in the verbal explanation or in gestures. This description could be well adapted to the episode we have described, in which the two representations proposed by the tablet, arrows and springs, were present in the apprentice's hand gestures and speech and successively integrated.
We also observed several episodes in which the two representations were not recognized as equivalent. Moreover, their incorrect or partial integration led to their misuse in the post-test, which introduced errors that were absent in the pre-test. The erroneous usage of the arrows in the post-test resembled the findings of Heckler (Heckler, 2010). The author reported that prompting students to draw free body diagrams increases the number of mistakes when students do not master this representation. In our study, we did not prompt apprentices but something similar happened. Some of them drew the arrows to make their own descriptions of the problems but they mechanically interpreted them according to the semantic used in StaticAR. What would have happened if these participants had drawn the springs together with the arrows? It is likely that they would have used the arrows in a redundant way, for example drawing inward arrows around a compressed spring. Of the two concepts included in the spring metaphor, namely the deformation and the consequent reaction, the deformation resulted to be too dominant and the arrows failed to activate the idea of reaction. As observed in the example reported in the paragraph about the force representation, some participants described the joints of a compressed beam as being pulled by the beam itself. Furthermore, the pinch and the spread gestures, which were used to convey the compression and elongation of the springs, made the misconception stronger because the reaction does not emerge from them. In order to handle these issues, both the augmentation and the learning activity could be improved. As regards the digital augmentation, probably the fact that the springs were placed at the centre of the beams gave the impression that they were floating, nothing was holding them and, therefore, there was no reaction. It might be better to place the springs either all along the beams or at their extremes. In this way the springs of connected beams are linked and this would highlight that there is interaction between them. From a different perspective, a more effective way to convey the idea of reaction of a single beam could be through other perceptual modalities than the visual one. Complementing the visual augmentation with haptic feedback could be one solution, as proposed in (Reiner, 1999; Wiebe et al., 2009; Han and Black, 2011). Another alternative that does not require special hardware could be the implementation of audio feedback (Roodaki et al., 2017). In this case, it would be interesting to investigate what would be a good sonification for the behaviour of the beams.
In terms of learning activity, it might be helpful to integrate our activity into a more com-

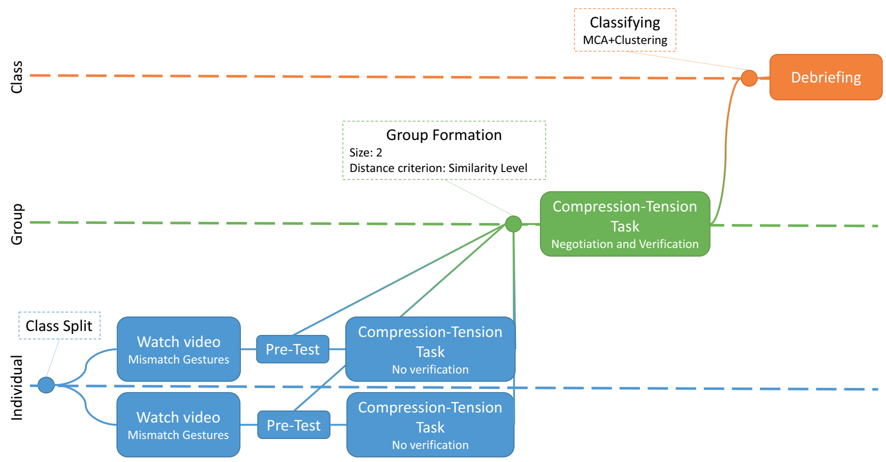


Figure 8.14 – Orchestration graph for a future scenario that includes the compression-tension task.

plex script of which the gesture-speech mismatch could become a functional part. The idea built on the study of Singer and Goldin-Meadow who investigated the effect of intentional gesture-speech mismatches when teaching mathematical equivalences to children (Singer and Goldin-Meadow, 2005). Children were taught about problem-solving strategies in three different ways: the explanations were not complemented by any gestures; teachers' gestures were conveying the same strategy described in speech; teachers' gestures and speech conveyed alternative strategies. The results showed that pupils who received the last treatment, namely the one based on the gesture-speech mismatch, achieved the highest average score in the post-test. The scenario that we proposed in formalized in Figure 8.14 as an orchestration graph (Dillenbourg, 2015). It begins with splitting the class in two groups. The apprentices from both groups would watch a video in which their teacher introduce them to the qualitative analysis of the structures. However, for one group the teacher's verbal explanations have mostly the beams as subjects while the gestures refers only to the forces acting on the joints. For instance, the sentence “The beam AC is in compression and consequently it pushes joints away” is followed by the hands moving apart. In the other video, the teacher does the opposite. Obviously this activity can be done outside the school time, for example the videos can be uploaded on Realto. Successively, the apprentices complete the statics' knowledge pre-test and then start the individual phase of the compression-tension task. The first group would work with the springs representation whereas the other would adopt the one with the arrows. Once they have completed the individual phase they forms pairs based on the similarity of the answers given in the pre-test. The activity proceeds like our SWISH script and eventually the final answers are clustered and become material for a whole-class debriefing.

Our analysis identified also other mistakes that could be attributed to two main causes: (1) wrong assumptions in picturing the deformations and the displacements; (2) lack of understanding of the types of support. In the first case, a learning activity centred around the

visualization of the deformation implemented in StaticAR could be effective to improve the apprentices' skill in visualizing non-rigid deformations. Considering that the spatial skills required for handling non-rigid mental transformations, described in (Atit et al., 2013), should be sufficiently developed during the carpentry training (Cuendet et al., 2014), what the apprentices probably need is to observe more instances of deformations and displacement of structures (Steif and Gallagher, 2004). In this direction, a new activity with StaticAR could be composed by several exercises each of which requires apprentices to predict the deformations of two-dimensional structures, to draw them and to compare them to solutions shown in StaticAR.
As regards the constraints and the boundary conditions imposed by the supports, we probably have underestimated the effect of the related graphical representations. In the statics knowledge test and in StaticAR, the supports are depicted with an abstract symbolism which is widely used to idealize their behavior. However, such abstract representations do not recall concrete instances that would help carpenters visualize the reactions. Furthermore, considering the importance of taking into account the supports when analysing a structure, it might be helpful to split the verification stage of the compression-tension task into two parts. The first one focuses only on the external loads and on the reactions given by the supports. Later, the results for the whole structures are displayed.

From a general perspective, even though we did not observe a neat learning gain, apprentices ended the activity wondering what is about the role of a zero-force member, realizing that they made a mistake because they thought a support to be fixed while it was rolling, asking why their reasoning was incorrect and so on. They had little prior experience about the topic but they used it to collaboratively generate and explore solutions to the problems. For example, we observed how participants found patters to answers the questions (e.g. triangles of forces), even though they were often unsuccessful in their efforts. Within the *preparation for future learning* framework (see subsection 2.3.3), this failure could turn to be *productive* if it is followed by a consolidation phase in which apprentices can contrast their ideas with canonical ones and engage in a discussion with experts and teachers (Kapur and Bielaczyc, 2012). Building on these observations, we conclude this section with the suggestion of a PFL scenario around the concept of zero-force member (Figure 8.15). The scenario begins by distributing three types of trusses without the internal web among apprentices, each apprentice receiving only one type of truss. The task consists in using StaticAR to design the internal web of the truss with at least 3 zero-force members. At this stage StaticAR shows only whether the structure is stable and does not collapse. The problem is open-ended and apprentices are free to add beams, change their materials and add supports. Once they finish with their design, they are grouped in pairs. Each pair is formed by apprentices who received the same type of truss but who created different topologies for the internal web. The criterion is to maximize the difference to create two contrasting cases. StaticAR shows the axial forces in the trusses. In case of mistakes, apprentices have three chances to collaboratively improve their designs and check the new solutions with StaticAR. In the next step, the designs are distributed among apprentices who receive a type of truss on which they have never worked

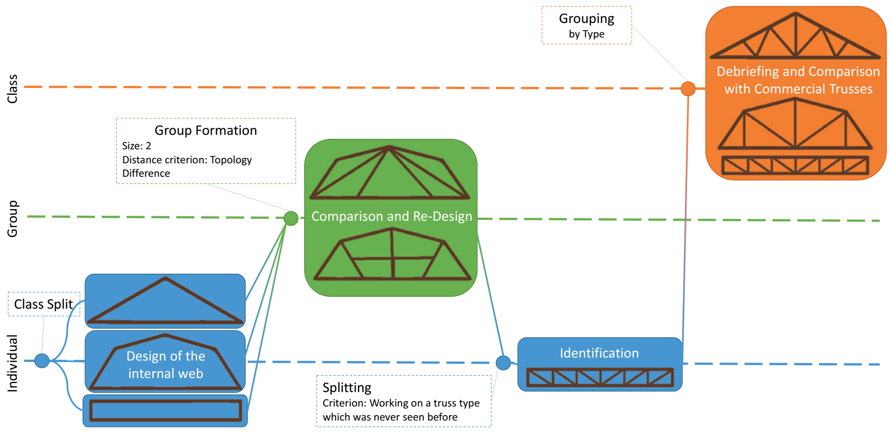


Figure 8.15 – Orchestration graph for PFL scenario about the concept of zero-force members.

in the previous phases (new contrasting case). In this individual step, the task consists in identifying the zero-force members in the internal web. In case of mistakes apprentices can give a new answer, up to three attempts. Lastly, the teacher receives the designs and initiate a class discussion confronting apprentices' designs with those of standard pre-build trusses.

8.5 Conclusions

We have presented a collaborative version of the tension-compression task in which pairs of apprentices used StaticAR to solve it. Although the pre/post-test comparison did not reveal any learning gain, the activity worked well: both apprentices and teachers saw the potentiality of the tool in being integrated in the curriculum.

Both the activity and the tool could be improved. The students found difficulties in understanding the relation between the two representations of the axial forces, arrows and springs, although we observed also cases of correct reasoning influenced by the two graphical notations. A result that deserves future investigation was that the outcome of the collaboration might benefit from pairing students with a similar level of prior knowledge. For these findings we suggested to integrate the script used for this experiment in a more complex one, in which the introduction to the concepts of the task becomes part of the SWISH design. Lastly, we summarized common mistakes from the apprentices by using unsupervised clustering methods and we proposed activities that could be implements directly within the current version of StaticAR.

9 General Discussion

These last sections summarize the findings from the four studies presented in order to highlight the contributions, the limitations and the opportunities that could inspire future research directions.

9.1 Roadmap of the Results

- **We found that the gaze measures we used confirmed some of the benefits associated to tangible interaction**. These are the facilitation of constructing the mental models of 3D shapes and of translating users' execution plan into interface actions. Even though we hypothesized that such benefits depended on the matching between the physical appearance of the tangible interfaces and their digital representation, we found that **the advantages persisted even when the digital-physical coupling vanished over time** and that users modified their task-solving strategies in order to mitigate the effect of this loss.

- From our comparative study, **it did not emerge any clear advantage in exploring statics concepts through the manipulation of interactive physical models**. Compared to the adoption of non-interactive models, the task performance and the learning gain did not significantly differ. In addition, **some elements of the interactive models could drive away the learners' focus from the areas relevant to the solution of the given problems**.

- In handheld AR systems, real-world objects that form the background for the augmentation also affect the users' experience, even when they are not explicitly designed to be functional to the systems. **Moving the visual attention from the device to physical objects sustains the users' spatial orientation within the digital and the physical spaces**. Furthermore, we found that the occurrence of shifts of visual attention was not influenced by the task difficulty, by the setup of the device or by users' spatial abilities, although these factors might affect some other characteristics like their duration.

- **The combination of two types of representations**, springs and arrows, that were developed to depict axial forces within a structure, **could effectively induce a correct intuition of statics principles when students worked collaboratively**. Nevertheless, difficulties in their interpretation were frequent and **we identified common issues exhibited by apprentices and proposed the implementation of new learning actives to address them**.

9.2 Contributions

9.2.1 Fostering an Intuitive Understanding of Statics

Can apprentices develop an intuitive understanding of statics without going into the mathematical formalisms? In other learning contexts, previous works have shown that this goal could be reached (described in Chapter 2). Hence, we believe that the answer to this question is still positive. The aim of this dissertation has been to explore how to fulfil our purposes within the vocational education context.

In our last study, the improvements observed in some apprentices indicated that our augmented reality environment can help in developing statics reasoning abilities, although it was not possible to show a significant learning gain. One might wonder whether there was any improvement compared to the performance achieved by apprentices in study presented in chapter 5. When looking at Figure 9.1 it is possible to notice that the relative learning gains were not statistically different in the four experimental conditions. Ironically, the highest median was found when apprentices worked with non-interactive structures and received the simple feedback “correct/incorrect” from the experimenters. Besides the concerns about the validity of the pre-test and post-test (see below), the two studies were not meant to prove the existence of one best solution. The first study has highlighted that activities meant to foster a conceptual understanding of statics did not necessarily benefit from hands-on exploration. The result was not novel and gave support to previous claims that the manipulation of physical tools does not guarantee learning (McNeil and Jarvin, 2007; Han et al., 2009; Alfieri et al., 2011). Our contribution has been to show the reason why this happened by comparing the gaze behaviors of apprentices and experts. The spring mechanisms that we designed to make the models interactive and to provide a visual feedback of the axial forces acting on them, absorbed participants’ attention at the expense of other parts of the models that experts took into account. These parts were relevant to understand how forces balanced each other and reached the equilibrium. On the contrary, the gaze behavior of apprentices who worked in the non-exploratory condition was closer to the experts’ one. Based on these results, we proposed the augmentation through StaticAR as a way to overcome the observed limitations. The presence of small-scale wooden models remained a crucial aspect of our AR environment, but we chose not to pursue the idea of augmenting interactive structures after weighting up the findings and other factors, like the time to manufacture them and its cost, following the suggestion in (Klahr et al., 2007). Nevertheless, adopting StaticAR in combination with interactive models definitely deserves future explorations and it is likely that apprentices would benefit from a hybrid approach of augmented reality and manipulative tools.

The visualizations available in StaticAR "reveal the invisible" and go obviously beyond what physical models can show. The tool allows apprentices and teachers to quickly run simulations. The many parameters usually required to setup the structural analysis scenarios (like Young's modulus, moment of inertia, etc.) emerge from the interface in the form of wood species, timber strength class and size of rafters, something that have a concrete meaning in carpentry. As we could only study a part of the several functions and visualizations available, we chose those related to the analysis of the axial forces which is relevant to the study of roof structures. We decided to keep the springs in the digital augmentation because they show the nature of such forces (compressive and tensile) in an intuitive way, but we combined them with a slightly more formal representation, namely arrows. The arrows would convey the way forces interact and reach the static equilibrium which were the aspects that the spring mechanisms of chapter 5 did not express to apprentices. To investigate whether this combination would work, we created an activity in which pairs of apprentices used the two representations to collaboratively solve statics problems. The outcome of the collaboration was not constant, but in several occasions apprentices' explanations reflected the intuition of statics principles. The study has also the merit of identifying part of the difficulties and misconception encountered by apprentices. To our knowledge, this has been rarely investigated in the vocational domain. Taxonomies of the typical errors made by students who start approaching statics, and more generally classical physics, are only available for high school and undergraduate students (Steif and Dantzler, 2005). In this sense, we have provided additional information to better shape the instructional materials available to apprentices and vocational teachers.

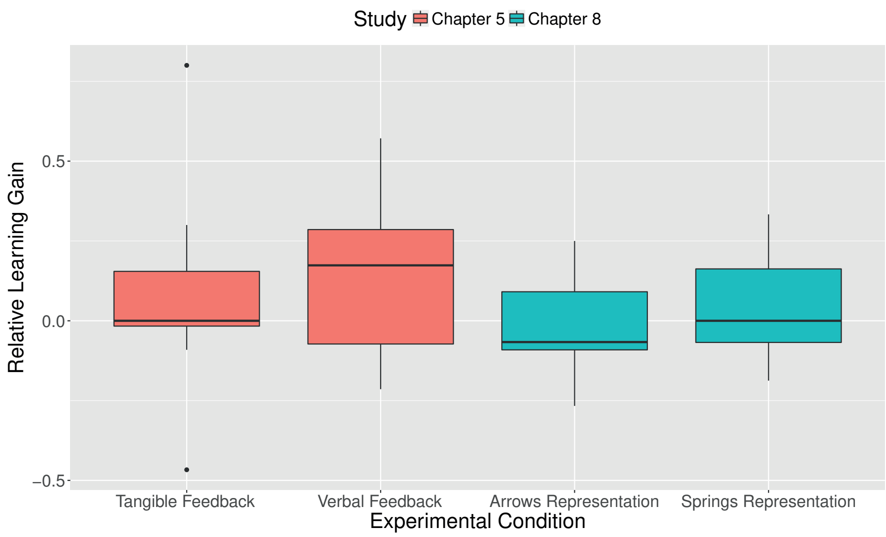


Figure 9.1 – Relative learning gains in the studies of chapters 5 and 8

9.2.2 The role of physical objects in AR systems

We have been able to provide empirical support for the positive impacts that tangible interaction could have on users' experience as described by other authors (Marshall, 2007; Antle and Wise, 2013). The contribution came mainly from the application of the eye-tracking methods that has recently become more common in research areas of tangible interaction and TUIs (Schneider et al., 2015, 2016). In particular, the claims that attribute to tangibles the advantage of promoting a more readily comprehension of 3D shapes compared to digital visualizations found confirmation in our third study too (the one about the shifts of visual attention). Even though in that setup the manipulation of the physical structures did not have any effect on the AR experience, one of the findings was that the aid associated to the perception of complex geometries was reflected in a higher number of fixations in the participants' gaze when they were looking at challenging structures.
In both the studies of chapters 4 and 7, the participants worked within mixed-reality environments where they needed to link the virtual and the real-world spaces. The study of chapter 7 confirmed that this connection could be facilitated by the physical entities since they exist in both spaces and act as anchors and spatial cues. Gaze-shifts were due to participants' change of position and it is very likely that the same motivation brought participants in the study of chapter 4 to look at the physical shape. In that case, the anchoring function was even more precious because in the experimental setup the physical space (the workspace printed on paper) and the digital space (the screen) were not overlapping. The issue of sustaining users' spatial perception is well known in mixed-reality research, especially for what concerns the design of immersive environments where the user cannot rely on natural multi-sensory during locomotion (Darken and Peterson, 2001). In outdoor environment it has been shown that looking at the real-world surroundings and introducing artificial spatial cues in the AR applications help users to keep the spatial orientation. (Veas et al., 2010; Tatzgern et al., 2015). Our findings suggested the possibility to use physical objects as spatial cues in indoor mixed-reality systems too.

Another result from the first study was that participants kept on referring to the physical interface even when its shape began to diverge from the shape of its digital counterpart, which made us reject our *tokenization* hypothesis. This finding should be discussed in the light of the fact that tangibles usually cannot accommodate the changes of their digital representations (few exceptions like (Follmer et al., 2013)). As a consequence, in application where the digital entities mutate (e.g. CAD) either the digital shape changes according to the physical one or the tangibles are mere controllers (examples in (Marner and Thomas, 2010; Wendrich and Kruiper, 2017)). We showed that tangibles can keep their representational role in this kind of applications too, in the sense that, even when the physical correspondence is partially lost, they embed the properties of the digital representations that go beyond the properties of tokens (presence, position, proximity). Furthermore, the loss of physical correspondence was, to some extent, actively avoided by the participants. Our tangible interface could not accommodate the changes of its digital representation, so participants changed their task-solving strategy in order to preserve that part of information they probably could not reconstruct from somewhere else. Therefore, the question is how to identify these properties and the users' purposes that they serve. A guideline is to design the experimental tasks in such a way that there is a straightforward and obvious strategy that nullifies the hypothesized advantage. Since users are quite reluctant to lose the advantage, alternative strategies would emerge. From our experience, we hypothesize that the aforementioned anchoring role does not dissolve when relaxing the correspondence between physical and digital shapes. Similarly, we believe that a complete physical representation is not required to build a mental model when working with an object made of symmetrical pieces. As resulted form the interviews in chapter 7, the real object could be reduced to just one of symmetrical pieces.

9.3 Limitations

The design of StaticAR would have profited from having the vocational teachers more involved in it. However, the problem of introducing statics was novel and only recently teachers started to have a better idea of its facets. As a consequence, with StaticAR we have tried to anticipate, to some extent, what would be needed in the future. Several features, as well as their potential employment in learning activities, have remained untested. In terms of usability, we could see that StaticAR worked well when the apprentices worked in pairs and their teachers feedback were positive. Nevertheless, the activity still resembled too much an experiment rather than a class activity. Another aspect we could not study was whether StaticAR is a teaching tool or a learning tool. We believe it could serve both purposes. The tension-compression task was definitely meant to be part of a learning activity, but the default visualizations can be used by teachers during a lesson. In conclusion, we see a clear need for studying in which conditions a classroom activity would work well and which tools should be introduced to assist teachers in this task.

Assessing the learning gain was difficult too. We have created the statics knowledge test and the compression-tension task with the help of carpentry teachers, but we could not thoroughly evaluate to what extent the performance in the test and in the task reflects apprentices' level of intuitive understanding and its development. The current version of the statics knowledge test covers only the analysis of truss structures for which it provides a coarse assessment of apprentices' abilities. The single questions are not tuned to provide a measure of how well a topic is mastered, for instance the knowledge of the types of supports and the understanding of the load directions. Furthermore, it advantages those apprentices who work in contact to this type of structures because the pictorial representations recall familiar scenarios. A carpenter who manufactures spiral staircases would probably manifest an intuitive understanding of statics that does not get triggered by a pictorial representation of a roof structure. It follows that the test should be extended to encompass questions about other topics besides trusses, such as bending of beams and displacements. Obviously, this would increase its duration and make more difficult to run interventions in the short time that teachers can spare to explore novel solutions. Lastly, in chapter 5 we also noticed that participants' spatial skills were correlated with their score of pre-test, done on paper, but not to their score in the intervention, done on physical structures. This also raises questions about the choice of appropriate media for the test.

The development of StaticAR has been informed by data collected in the carpentry training context. Teachers and apprentices who were involved in our design process came from the same population and we tailored tasks and functions of StaticAR for the the carpentry world. It seems reasonable to wonder whether our findings are generalizable to other vocational professions.

Apprentices could be more motivated in exploring the physics of structures if they could bring to the classroom the structure on which they are working. This would create the flow of experiences described in the Erfahrraum (see chapter 6). The app presented in the same chapter, which allows apprentices and teachers to draw structures and create the configuration files for StaticAR, represents part of our effort that went into setting this flow of experiences in motion. We have an ecosystem of tools (StaticAR, drawing app, Realto) that, in principle, should create resources able to cross the boundary of the contexts in which apprentices learn. Due to project constraints, the evaluation of the bottlenecks in the above process has been left for future work.

9.4 Future Research Directions

It is not hard to imagine that part of the work that could be done in the future naturally comes from the limitations we have just discussed. One future direction would be to create a vocational statics concept inventory: a set of instruments to assess the level of intuitive understanding of statics. We used Multiple Correspondence Analysis to extract clusters of students who had the same difficulties, however some clusters could hardly be interpreted. Having a more powerful instrument becomes crucial for any researcher who pursues objectives similar to ours. An interesting opportunity is to implement such tools using an augmented reality system like StaticAR, which would overcome the bias that affects paper-based tests related to differences in participants' spatial abilities. It would also bring the advantage of keeping a digital trace of apprentices' states that can be used, as proposed in the orchestration graph in chapter 8, as criterion to form groups in classroom activities.

We imagined StaticAR as an environment in which apprentices enter, get instructions about the topic and the task on which they will work, take an activity and hopefully develop some correct qualitative understanding. This is an ambitious goal that could drive future extensions of our work. However, the last study highlighted the potential of StaticAR as a preparation for future learning tool (PFL, subsection 2.3.3). Our activity made apprentices' curiosity arise, pushed them to reflect on their answers and made them realize their mistakes without necessarily achieving any learning gain in the traditional sense (pre/post-test comparison). These observations brought us to design a possible PFL scenario in which StaticAR would support apprentices' elaborations and explorations so that they could be ready to attend class lectures. Compared to the initial goal, this aim looks less ambitious. Nevertheless, if gaining a conceptual understanding of statics benefits from a PFL approach, the role of StaticAR would be more modest, but it would still remain a precious learning resource.

Considering the hype around mixed-reality systems and their application to the learning domain, a question that might puzzle designers and developers is to what extent the real-world should be made accessible. It is also a question of where to place a system in the reality-virtuality continuum (chapter 2) and what type of roles physical representations or the physical surroundings are expected to have. Design guidelines are largely available in literature, but new opportunities are offered by commercial solutions. What would be the impact of exploring statics in a more immersive environment instead of using a handheld device?

In conclusion, we focused on how augmented reality could foster an intuitive understanding of statics and, within this subject, much remains to uncover. We believe that other subjects would benefits from the same approach: gaining an intuitive understanding of the acoustic properties of the materials, of the thermal properties and so on. Vocational curricula include STEM topics, but the peculiarities related to teaching and studying them as vocational teachers and apprentices would do are under-represented in vocational research, and so are learning technologies. According to our experience, this is the perfect time for studying the impact of AR tools in vocational classrooms: the required hardware is affordable, students are already familiar with it and high ecological validity is almost guaranteed. Augmented reality has turned into a modest technology, which could be introduced in the current practices without making a learning activity an exceptional activity anymore.

Appendices

A Appendix to Chapter 4

A.1 Questionnaire

Name: **Surname:**

Age: **Gender:** M F

EPFL Section: **Year:**

What is your level of familiarity with CAD softwares (ArchiCad, AutoCad,ScketchUp...)

No Knowledge Beginner Intermediate Advanced

How many hours per week do you spend using these softwares

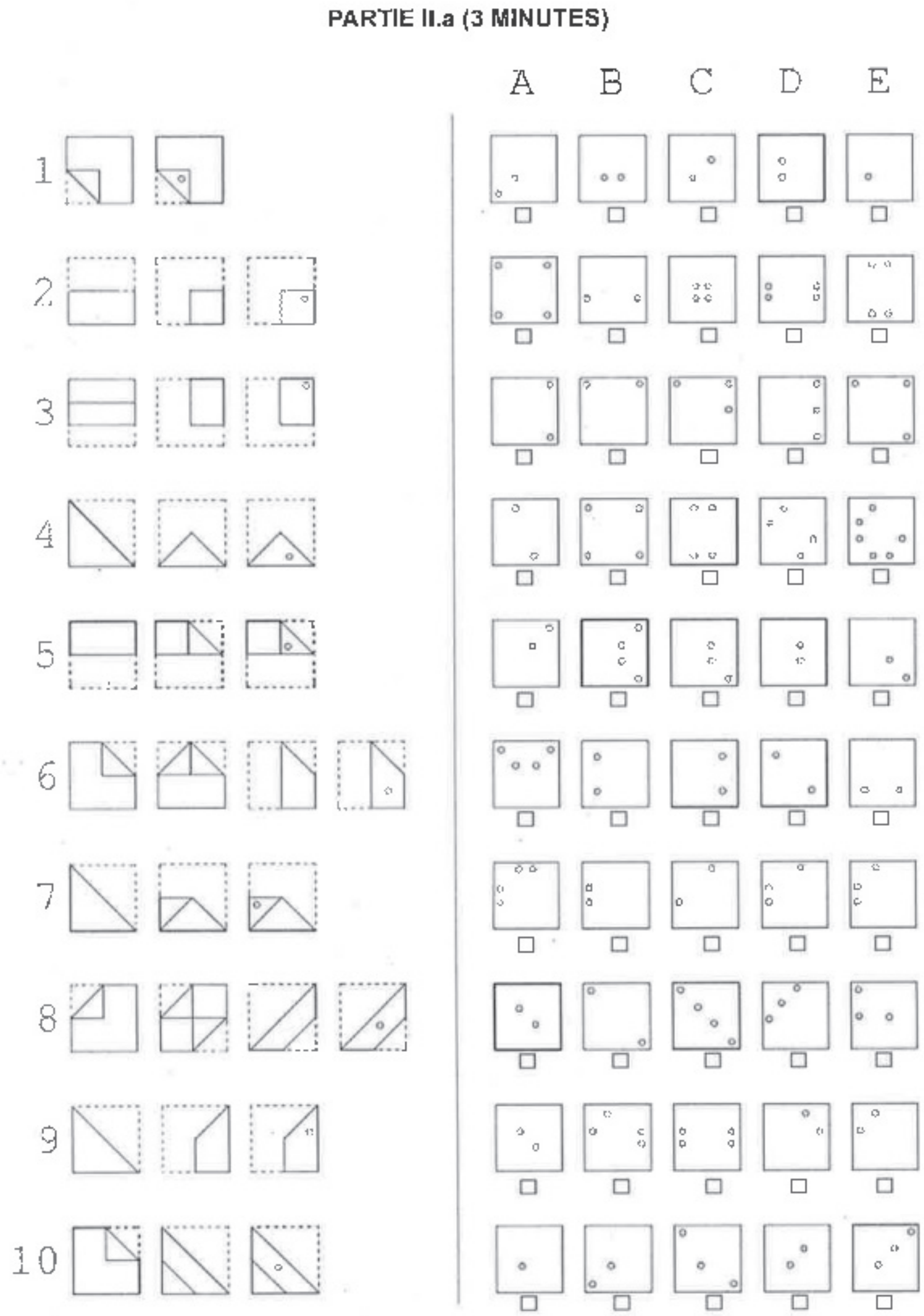
Less than 7 7-14 14-21 21-28 more than 28

Do you play 3D videogames? **Yes** **No**

How many hours per week do you spend playing 3D videogames?

Less than 7 7-14 14-21 21-28 more than 28

A.2 Paper Folding Test



B Appendix to Chapter 5

B.1 Presentation Page

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Datum/Zeit:

A Study of Carpenter's Static Reasoning Skills:

External Load Distribution in Roof Structures

Liebe(r) Teilnehmer(in),

vielen Dank für die Teilnahme an unserer Studie!

In diesem Experiment geht es um einige grundlegende Konzepte der Statik. Es besteht aus drei Teilen: Einem Prätest, der eigentlichen Aufgabe und einem Posttest. Für jeden Teil gibt es ein Zeitlimit.

Der Prätest selbst besteht aus zwei Teilen. Zu Beginn jedes Abschnitts findet sich eine Erklärung der nächsten Aufgabe. Bitte beantworte so viele Fragen wie möglich, aber es ist normal, dass Du nicht alle Fragen beantworten kannst. Wenn Du mit einer Frage nicht weiterkommst, gehe zur nächsten über.

Deine Daten sind sehr wichtig für uns. Bitte beantworte die folgenden Fragen gewissenhaft. Die Daten werden anonymisiert verwendet und können nicht zurückverfolgt werden.

Falls Fragen aufkommen, zögere nicht den Versuchsleiter zu fragen!

B.2 Demographic Data

Identifikationsnr.:________

Demografische Daten:

Bitte beantworte folgende Fragen.

Geschlecht: ○männlich ○weiblich
Alter: ___
Ausbildungsjahr: ___
Höchster Schulabschluss: ____________________

Wie vertraut ist dir der Umgang mit statischen Konzepten allgemein?
○sehr vertraut
○vertraut
○mehr oder weniger vertraut
○begrenzt vertraut
○fremd

Wie vertraut ist dir der Umgang mit Kräften, die auf eine Dachkonstruktion einwirken?
○sehr vertraut
○vertraut
○mehr oder weniger vertraut
○begrenzt vertraut
○fremd

Wie oft spielst du das *Bridge Building Game* oder benutzt eine Simulationssoftware für Statik? (oder etwas Vergleichbares: ______________).

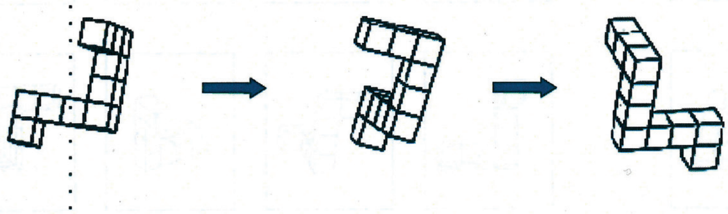
○sehr häufig
○oft
○manchmal
○kaum
○gar nicht

B.3 Presentation of the Mental Rotation Test

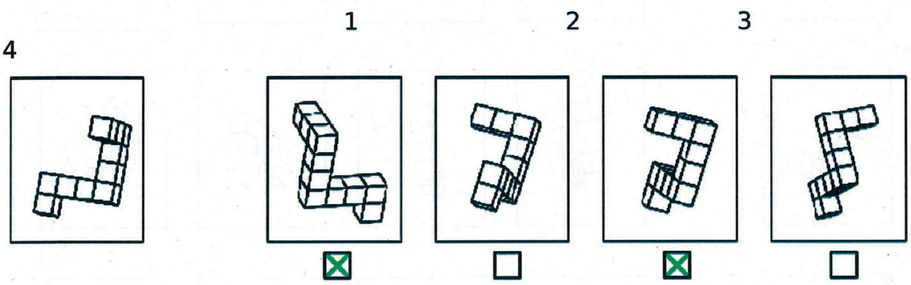
Identifikationsnr.:________

Prätest: Teil I

Bitte betrachte das linke Objekt auf dem folgenden Bild. Stell dir vor, dass es nur um seine **vertikale Achse** rotiert werden kann. Die rechten Objekte zeigen zwei mögliche Positionen des ersten Objektes, nachdem dies um seine vertikale Achse gedreht wurde.



In diesem Abschnitt des Prätests wirst du **12 Fragen** beantworten, die dem folgenden Beispiel entsprechen. Hier stimmen Bild 1 und 3 mit dem Zielobjekt links überein, nachdem dieses um die vertikale Achse rotiert wurde.



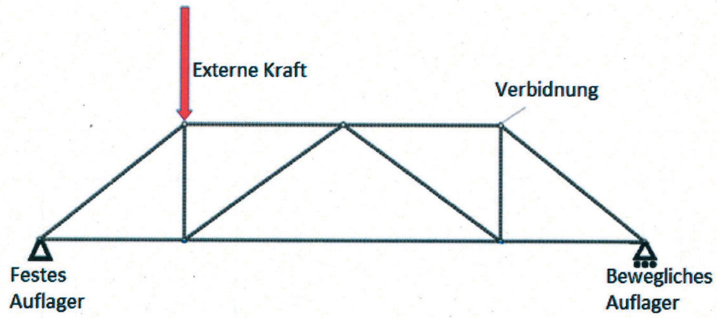
Während du den Test bearbeitest, bitte denk daran dass in jeder Aufgabe **ZWEI und nur zwei** Figuren dem Zielobjekt entsprechen. Du bekommst nur dann einen Punkt, wenn du **beide korrespondierenden Figuren** markierst. Wenn du nur eine Figur ankreuzt, erhältst du keinen Punkt.

Du hast **3 Minuten** Zeit um **12 Fragen** zu beantworten.

B.4 Statics Knowledge Test

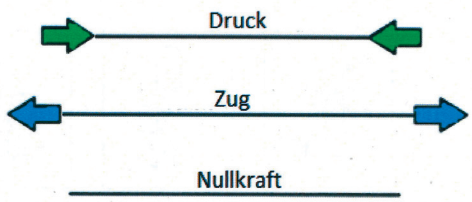
Prätest: Teil II - Einführung: Zug, Druck und Nullkraft

Ein Fachwerk besteht aus einzelnen Elementen, die an ihren Endpunkten **verbunden** sind. Die **Auflager** können entweder fest oder beweglich sein.



Wenn eine externe Kraft auf das Fachwerk einwirkt, dann wirkt Kraft am Ende jedes Elements **entlang seiner Achse**. In diesem Experiment berücksichtigen wir die folgenden Kräfte:

- ***Druckkraft***: Kraft, die dazu neigt, das Element zu verkürzen
- ***Zugkraft:*** Kraft, die dazu neigt, das Element zu verlängern
- ***Nullkraft***: Es wirkt keine Kraft auf das Element

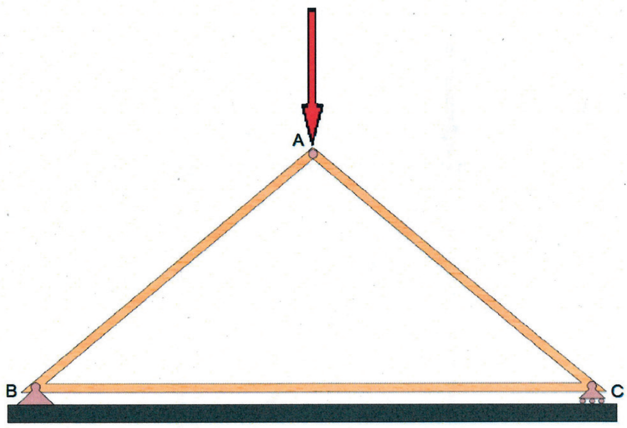


Nachfolgen wirst Du sieben Bilder verschiedener Fachwerke sehen. Auf jedes Fachwerk wirken ein oder mehrere externe Kräfte ein. Bitte bestimme für die genannten Elemente, ob sie unter Zug-, Druckkraft oder keiner Kraft stehen.

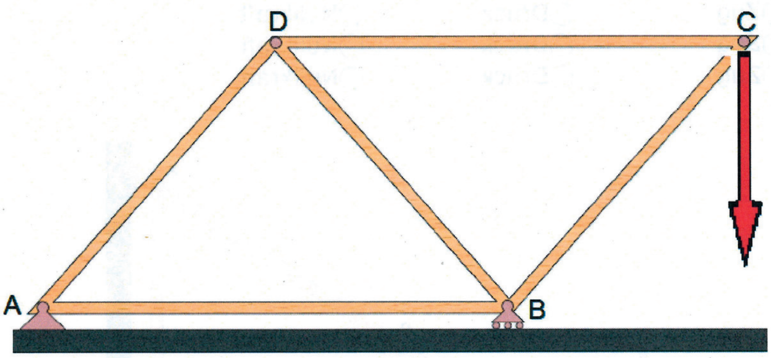
Für diese Aufgabe ist die Stärke der Kraft zu vernachlässigen. Wenn mehrere Kräfte auf ein Fachwerk einwirken, so haben sie dieselbe Stärke. Bitte beachte, dass die Elemente nicht verformbar sind und ihr Eigengewicht keine Rolle spielt. Achte zudem auf die verschiedenen Auflager.

Du hast **9 Minuten** Zeit, um **7 Fragen** zu beantworten.

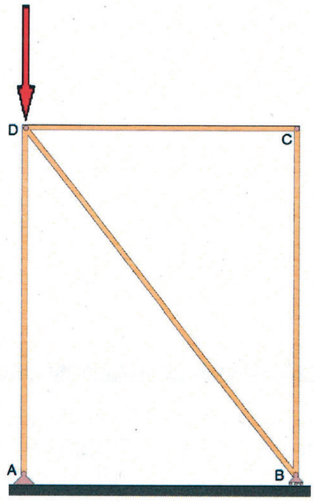
Prätest: Teil II



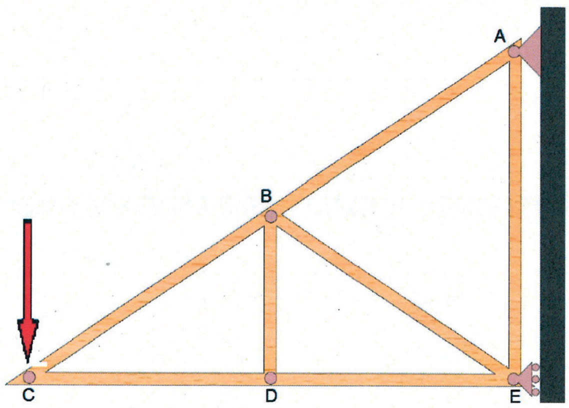
AB: ◯Zug ◯Druck ◯Nullkraft
AC: ◯Zug ◯Druck ◯Nullkraft
BC: ◯Zug ◯Druck ◯Nullkraft



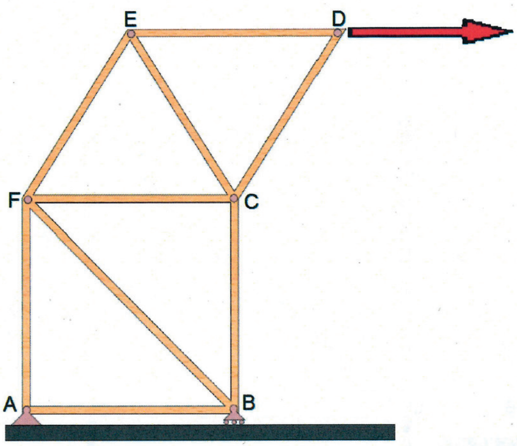
AB: ◯Zug ◯Druck ◯Nullkraft
AD: ◯Zug ◯Druck ◯Nullkraft
BC: ◯Zug ◯Druck ◯Nullkraft



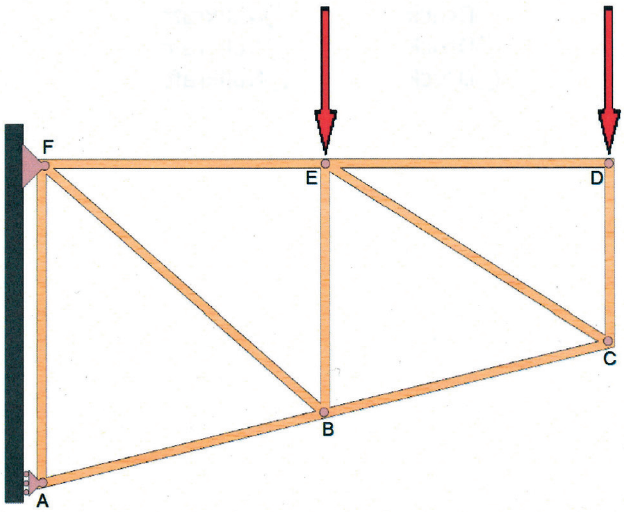
AD: ◯Zug ◯Druck ◯Nullkraft
BC: ◯Zug ◯Druck ◯Nullkraft
BD: ◯Zug ◯Druck ◯Nullkraft



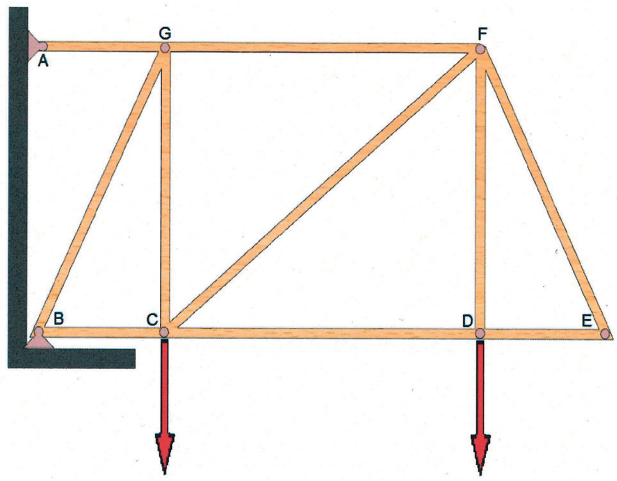
BD: ◯Zug ◯Druck ◯Nullkraft
AB: ◯Zug ◯Druck ◯Nullkraft
AE: ◯Zug ◯Druck ◯Nullkraft



AB: ◯Zug ◯Druck ◯Nullkraft
CD: ◯Zug ◯Druck ◯Nullkraft
BF: ◯Zug ◯Druck ◯Nullkraft



BC: ◯Zug ◯Druck ◯Nullkraft
DE: ◯Zug ◯Druck ◯Nullkraft
BF: ◯Zug ◯Druck ◯Nullkraft



AG: ◯Zug ◯Druck ◯Nullkraft
CD: ◯Zug ◯Druck ◯Nullkraft
EF: ◯Zug ◯Druck ◯Nullkraft

C Appendix to Chapter 6

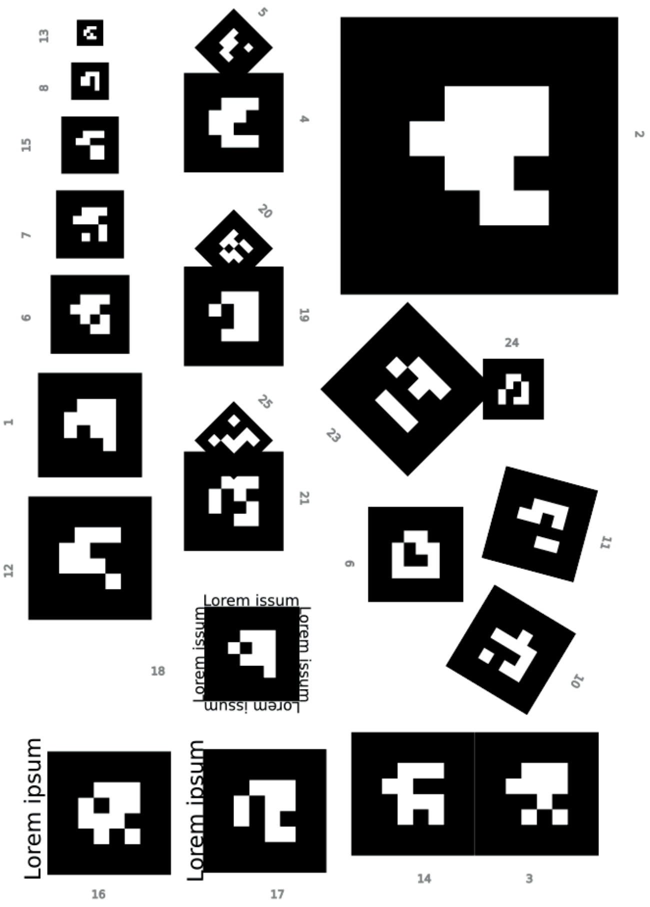
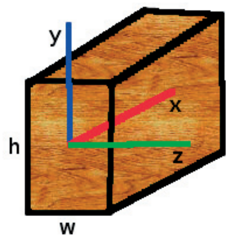


Figure C.1 – Input image used for the comparison of the marker detection libraries.

Table C.1 – Mechanical Properties for Solid Rectangular Beams

Variable Name	Symbol	Formula
Cross-sectional Properties		
Section Width	w	-
Section Height	h	-
Cross-sectional area	A_x	$w \times h$
Shear area in local y-axis	A_y	$\frac{2}{3}A_x$
Shear area in local z-axis	A_z	$\frac{2}{3}A_x$
Torsional moment of inertia	J_x	$\left(\frac{1}{3} - \frac{0.224}{\frac{h}{w}+0.161}\right) hw^3$
Moment of inertia for bending about y-axis	I_y	$\frac{hb^3}{12}$
Moment of inertia for bending about z-axis	I_z	$\frac{bh^3}{12}$



Variable Name	Symbol	Formula
Material Properties		
Modulus of elasticity	E	-
Shear Modulus	G	-
Density	ρ	-
Resistance to bending	f_m	-
Resistance to tension parallel to grain	$f_{t,\parallel}$	-
Resistance to tension perpendicular to grain	$f_{t,\perp}$	-
Resistance to compression parallel to grain	$f_{c,\parallel}$	-
Resistance to compression perpendicular to grain	$f_{c,\perp}$	-
Resistance to shear parallel to grain	$f_{s,\parallel}$	-

Table C.2 – Quantities output by the statics kernel. For the beams, the *peak* location refers to the greatest absolute value for the quantity, whereas the location *segment i* refers to the value at the segment i of length 10mm.

Element	Quantity	Symbol	
Joint	Displacement along x axis (same for y and z axes)	D_x^j	
	Reaction Momentum along x axis (same for y and z axes)	M_x^j	
	Reaction Force along x axis (same for y and z axes)	R_x^j	
		Location	
		Peak	Segment i
Beam	Moment along x axis (same for y and z axes)	M_x^p	M_x^i
	Axial	N^p	N^i
	Shear along y axis (same for z axis)	τ_y^p	τ_y^i
	Displacement along x axis (same for y and z axes)	D_x^p	D_x^i

Table C.3 – Stress Types and the Formulas used to compete the stress in relation to the material.

Stress Type	Relative Stress Formula
Axial Stress	$(N^p/A_x)/f_{t,\parallel}$ if N^p is a tensile force $(N^p/A_x)/f_{c,\parallel}$ if N^p is a compressive force
Bending stress	$\max\left(\frac{6M_y^p}{wh^2}, \frac{6M_z^p}{hw^2}\right)\Big/ f_m$
Shear stress	$\max\left(\tau_y^p/A_y, \tau_z^p/A_z, M_x^p/\beta h w^3\right)\Big/ f_{s,\parallel}$, where β depends on the ratio h/w

h/w	1.0	1.5	2.0	2.5	3.0	4.0	5.0	6.0	10.0	∞
β	0.141	0.196	0.229	0.249	0.263	0.281	0.291	0.299	0.312	0.333

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Lorenzo Lucignano

Interests

Human-Machine Interaction, Intelligent Agents, Post-WIMP interfaces, Mixed Reality, Computer Vision

Education

2013–2018 **PhD in Computer Science**
École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland
- Thesis Title: Augmented Reality for Facilitating a Conceptual Understanding of Statics in Vocational Education
- Topics: Augmented Reality; Learning Technology; Human-Computer Interaction; User Studies

2010–2013 **Master in Computer Science**
Universitá degli studi di Napoli Federico II, Naples, Italy
- Major Subject: Artificial Intelligence
- Thesis Title: A Dialogue Manager For Multimodal Human-Robot Interaction
- Topics: Human-Robot Interaction; Dialogue Management; Markov Processes
- Final Grade: 110/110 cum laude

2006–2010 **Bachelor in Computer Science**
Universitá degli studi di Napoli Federico II, Naples, Italy
- Thesis Title: Implementation and analysis of an optical mouse based on 3D planar tracking
- Topics: Computer Vision
- Final Grade: 110/110

Experience

Research Experience

2013–2018 **Doctoral Researcher**
Computer-Human Interaction in Learning and Instruction Laboratory, EPFL, Lausanne, Switzerland
- Research
  - **Design and Development:** Built an augmented reality system to support the learning of statics in an intuitive way (video).
  - **User Studies:** Designed and conducted several studies centred around the design of the aforementioned system employing also eye-tracking methods
  - **Qualitative and Quantitative Data Analysis:** Performed a wide variety of analysis of the gathered data, including coding of dialogues and think-aloud sessions, statistical inference, correspondence analysis and clustering
- Projects
  - Leading House DUAL-T, a research project focusing on learning technologies for the Swiss vocational education system (link)
- Other Activities
  - Teaching assistant in four BSc and MSc courses.
  - Coordinator for the course "Introduction to visual computing" during the spring semester 2015, 2016 and 2017
  - Supervision of four semester students

August 2013 **Research Assistant**
Department of Electrical Engineering and Information Technology (DIETI), Universitá degli studi di Napoli Federico II, Naples, Italy
Objective: Improvement of the dialogue manager described in the master thesis

Miscellaneous

Summer 2016 **Freelance Developer**
Prof. Jean-Luc Gurtner, Département des Sciences de l'éducation, Université de Fribourg, Fribourg, Switzerland
Development of a Windows application (Qt/C++/Qml) for a research study.

Fall 2012 **Instructor**
Voluntary organization "Un uovo mondo", at XII CIRCOLO DIDATTICO NAPOLI OBERDAN, Naples, Italy
In charge of an after-school program to introduce primary school students to the design and programming of Lego Mindstorm robots.

Computer skills

Languages C, C++, QML, Java

Frameworks Qt — Windows, Linux and Android development

Statistical Tools R

CAD SolidWorks, Blender (mostly to design for 3D printing)

Others LaTeX, ELAN, Git, OpenCV

Languages

Italian **Native speaker**

English **Upper-Intermediate** *ESOL B2 2012*

French **Beginner**

Projects

qml-Artoolkit
A wrapper to create augmenting reality applications in QT using ARToolkit. Github code

qtphysics-unofficial
A wrapper to use the physics engine Bullet in Qt3D-based applications. Github code: `https://github.com/chili-epfl/qtphysics-unofficial`

Awards and Fellowships

Spring 2015 EPFL IC School Teaching Assistant Team Award for the course "Introduction to visual computing"

2013–2014 EPFL IC School Fellowship

Publications

Lorenzo Lucignano and Pierre Dillenbourg. Double reality: Shifting the gaze between the physical object and its digital representation. In *International Symposium on Mixed and Augmented Reality, ISMAR 2017 Adjunct, Nantes, France, October 9-13, 2017, publishing*. IEEE, 2017.

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Other Interests

Maker (3D Printing, Arduino, RasberryPi), Gardening, Manufacturing Nativity scenes from raw materials