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Hybrid Craft Training in Vocational Education: Integrating E-Learning and VR in Glassblowing Apprenticeships

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Abstract

This article investigates how an e-learning platform and a virtual reality (VR) workshop simulator can be integrated into a traditional craft apprenticeship without displacing workshop-based learning. Drawing on the Craeft glassblowing Pilot 1 at CERFAV, it reports a two-phase mixed-methods study contrasting a Traditional Augmented (TA) group, which used a Craeft e-learning platform and a VR glassblowing simulator, with a Traditional (T) control group following the standard Certificate of Professional Competence (CPC) programme. Quantitative data from formative assessments and CPC examination results are combined with qualitative feedback, satisfaction surveys, self-assessment questionnaires, and interviews with apprentices and trainers. In Phase 1, where digital tools were deployed in a separated mode alongside existing instruction, the e-learning platform was perceived as pedagogically valuable, but effects on assessment outcomes were limited and uneven, with greater score dispersion in the TA group. In Phase 2, redesigned hybrid usage scenarios assigned distinct and complementary roles to the e-learning platform, VR, and workshop practice within an iterative learning cycle, yielding more consistent advantages for the TA group in cross-cutting theoretical subjects and reducing variance in their scores. Qualitative analyses show that apprentices adopt a pragmatic stance towards digital tools, using the e-learning platform primarily for revision and exam preparation and VR for workshop discovery and tool recognition, while maintaining a strong attachment to material practice. The study concludes that, in small, high-stakes craft VET programmes, the impact of virtual learning environments depends less on their intrinsic properties than on their orchestration within coherent hybrid designs and on trainers' capacity to align them with authentic tasks and assessment regimes.

Keywords: vocational education and training (VET); hybrid learning; blended learning; e-learning platform; virtual reality (VR); glassblowing; cognitive load theory; situated learning

1. Introduction

Craft occupations such as glassblowing rely heavily on tacit, embodied knowledge, the black box of experiment, traditionally transmitted through practical apprenticeship and an intensive workshop-based training. Within European vocational education and training (VET) systems, this mode of learning has come under increasing pressure from broader digitalization agendas and expectations that VET should integrate e-learning, simulations, and other digital tools to improve flexibility, efficiency, and access. At the same time, there is a growing recognition that in practice-oriented fields, digital technologies must complement rather than replace authentic material engagement if they are to contribute meaningfully to skill formation.

Recent work on blended and hybrid learning in VET suggests that combining online and face-to-face modalities can support learner autonomy, engagement, and workplace readiness, provided that instructional design is carefully aligned with occupational demands. Studies on virtual and extended reality environments in vocational contexts report benefits for safe practice, exposure to complex equipment, and the rehearsal of rare or hazardous situations, while also emphasizing that simulations need to be embedded in coherent pedagogical scenarios and supported by VET instructors. However, empirical evidence remains limited for traditional craft domains where the feel of materials, the micro-dynamics of bodily movement, and the situated interplay between craftsperson, tools, and environment play a central role in learning. In such contexts, the question is not simply whether digital tools "work" in general, but how they are appropriated by apprentices and trainers within the specific temporal rhythms, assessment regimes, and identities of craft VET programs.

Glassblowing is a paradigmatic example of an embodied craft taught through apprenticeship in dedicated training centers and workshops. In France, the "Centre Européen de Recherches et de Formation aux Arts Verriers (CERFAV)" offers a two-year alternating program preparing apprentices for the Certificate of Professional Competence (CPC), combining periods in companies with intensive "clusters" of center-based instruction. As part of the Horizon Europe project Craeft ("Craft Understanding, Education, Training, and Preservation for Posterity and Prosperity"), CERFAV implemented an experimental intervention (Pilot 1) to investigate the impact of digital tools on the learning process of second-year glassblowing apprentices. The intervention introduced two main digital components: an e-learning platform offering multimodal resources and assessments for cross-cutting theoretical subjects (e.g., general technology, health, safety and environment, technical drawing), and a virtual reality (VR) glassblowing workshop simulator designed to familiarize apprentices with the layout, tools, and basic operations of the hot shop.

Pilot 1 was organized into several phases aligned with the calendar of second-year clusters and contrasted a "Traditional Augmented" (TA) group, which used the Craeft digital tools alongside existing training activities, with a "Traditional" (T) control group, which followed the standard program and had access only to pre-existing digital resources (such as FabLab equipment). Across multiple clusters, apprentices in the TA group participated in project presentations, guided and autonomous use of the e-learning platform and VR simulator, and individual project follow-up interviews, while both TA and T groups were monitored through formative assessments and a final CPC examination. Data collection combined quantitative measures (formative assessment scores in cross-cutting subjects and CPC exam results) with qualitative materials including on-the-spot feedback, satisfaction surveys, self-assessment questionnaires, and semi-structured interviews with apprentices and trainers.

The initial analysis conducted within the Craeft project suggests a nuanced picture. On the one hand, apprentices generally perceived the e-learning platform as pedagogically valuable, particularly in terms of the quality of learning materials and support for exam preparation, and they recognized the VR simulator as a useful tool for orientation and preliminary practice. On the other hand, the impact of these tools on formal assessment outcomes appeared limited and uneven, with small and sometimes contradictory differences between TA and T groups, and a marked emphasis among apprentices and trainers on the continued centrality of direct material engagement in the workshop. Moreover, qualitative analyses revealed that learners tended to adopt a pragmatic stance towards digital tools, integrating them into their project work to the extent that they were perceived as useful, while also subcontracting complex digital tasks and foregrounding their relationship with the material.

These findings resonate with broader arguments in the VET literature that the benefits of blended and immersive technologies depend less on the tools themselves and more on the design of

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hybrid learning scenarios that connect digital activities to authentic practice. They also highlight the need to understand how such scenarios play out in real-world craft apprenticeship settings, where cohorts are small, programs are tightly structured around external examinations, and both learners and trainers must negotiate tensions between innovation and tradition.

Against this backdrop, the present article draws on the Craeft Pilot 1 glassblowing experiment to examine the integration of e-learning and VR tools in a formal craft apprenticeship program. Focusing on the second-year cohort at CERFAV, it seeks to characterize how apprentices appropriate these tools within the rhythm of their training, what kinds of learning outcomes can be observed in comparison with a traditional control group, and how participants articulate the relationship between digital and material dimensions of craft learning.

To address these aims, the study is guided by the following research questions:

- How do second-year glassblowing apprentices in a CPC program appropriate e-learning and VR tools when these are integrated into a hybrid training design during center-based clusters?
- What differences, if any, in learning outcomes emerge between apprentices who use hybrid digital tools (Traditional Augmented group) and those who follow traditional training only (Traditional group), as reflected in formative assessments and final CPC examination results?
- How do apprentices and trainers negotiate the tension between the introduction of digital tools and their strong attachment to material practice and workshop-based learning in glassblowing VET?

2. Background and Related Work

The present study sits at the intersection of three strands of research: theories of situated and embodied learning in vocational education, instructional design perspectives on cognitive load and multimedia learning, and empirical work on blended and immersive technologies in VET. This section briefly reviews each strand to situate the Craeft glassblowing pilot within contemporary debates on the digitalization of craft apprenticeships.

2.1. Situated Learning, Communities of Practice, and Craft VET

A substantial body of research has shown that learning in vocational and craft contexts is deeply situated in authentic activities, social relations, and material environments, rather than being reducible to the acquisition of decontextualized knowledge. Classic accounts of apprenticeship and communities of practice argue that novices learn through legitimate peripheral participation in shared work settings, gradually moving towards fuller participation as they internalize not only technical routines but also the values, identities, and tacit norms of the craft community [1]. In such perspectives, tools and artefacts are not neutral carriers of information but mediating structures that shape how knowledge is enacted and shared.

Traditional craft trades exemplify this situated, embodied character of learning. Ethnographic and practice-based studies of craft apprenticeship highlight the centrality of embodied demonstration, joint attention to material transformations, and subtle, multi-sensory feedback (visual, thermal, haptic, acoustic) in how skills are transmitted [2,3]. In glassblowing specifically, the dynamic relationship between the craftsperson's body, the viscosity of hot glass, the timing of rotations, and the affordances of workshop tools has been described as a form of "thinking in action" that cannot be fully externalized into verbal or textual representations [1]. This aligns with the argument, emphasized in the Craeft educational kit, that certain dimensions of "craftship", the black box of experiment, remain resistant to purely classroom-based or text-based instruction and require situational learning anchored in workshop practice [1].

Within European VET systems, such apprenticeship-based learning has increasingly been combined with school-based or center-based provision, creating hybrid institutional arrangements that must reconcile the temporal rhythms and assessment regimes of formal schooling with the open-ended, contingent nature of workshop learning [5]. In this context, the question is not simply whether digital tools can support learning in the abstract, but whether they can do so without displacing the centrality of material engagement that underpins professional identity and competence in craft occupations [1]. The Craeft project explicitly adopts this stance: digital tools are conceived as aids to be articulated with, rather than substitutes for, workshop-based learning.

2.2. Cognitive Load Theory and Multimedia / VR Instructional Design

While situated learning emphasizes the social and material embeddedness of knowledge, instructional design research brings a complementary focus on the cognitive architecture of learners and the conditions under which multimedia and immersive tools facilitate or hinder learning. Cognitive Load Theory (CLT) distinguishes between intrinsic load (stemming from the inherent complexity of the material), extraneous load (imposed by suboptimal instructional design), and germane load (devoted to schema construction) [6]. For complex domains such as glassblowing, where learners must coordinate multiple interacting elements (e.g. temperature, timing, tool use, body posture), CLT suggests that poorly designed digital resources can quickly overload working memory, whereas well-structured materials can help manage complexity and support the gradual automation of procedures [6].

Research on modality and redundancy effects further refines these claims. Studies have shown that presenting complementary information through multiple channels (e.g. narrated animation) can reduce cognitive load when each channel contributes unique elements, but that redundant or poorly synchronized information (e.g. identical text and speech) can increase load and impair learning [6–8]. These effects have been documented not only in traditional screen-based environments but also in immersive VR classrooms, where visual richness and interactivity can be beneficial but also risk distracting learners from core instructional cues [6,9]. In addition, the expertise reversal effect suggests that instructional formats that benefit novices (e.g. highly guided, worked examples) may become inefficient or even detrimental for more advanced learners, who need more open-ended problem-solving opportunities [6,10].

The Craeft educational kit explicitly mobilizes CLT and these related principles as design heuristics for its digital tools [6]. The quiz-first model implemented in the e-learning platform aims to activate prior knowledge and focus attention before the presentation of new content, while avoiding redundancy by distributing information across videos, diagrams, and textual explanations rather than duplicating it across modalities. Similarly, the glassblowing VR simulator is recognized as potentially helpful for reducing intrinsic load at the orientation phase (by familiarizing novices with spatial layout and tool names), but also as a possible source of extraneous load or redundancy for apprentices who already know the workshop and require fine-grained, haptic feedback for gesture refinement. This theoretical framing underpins the study’s focus on when and for whom digital tools are beneficial, rather than assuming uniform effects.

2.3. Blended and Hybrid Learning in VET

A third strand of research concerns the use of blended and hybrid learning in vocational and professional education. Numerous studies report that combining online and face-to-face modalities can support learner autonomy, engagement, and flexibility, particularly when asynchronous resources (e.g. videos, quizzes, simulations) are used to prepare for or extend in-person sessions [11,12]. In VET, blended approaches have been shown to facilitate the integration of workplace learning with school-based curricula, allowing apprentices to revisit theoretical content at their own pace and to link it more explicitly to workplace tasks [13].

However, the literature also warns that blended learning is not automatically effective: its impact depends heavily on instructional alignment, the clarity of task sequencing, and the extent to which online activities are meaningfully connected to assessments and workplace practice [11,14]. Studies in health, engineering, and technical trades emphasize that learners are quick to disengage from online components perceived as peripheral or duplicative, and that teachers often require substantial support to redesign courses in a way that fully exploits hybrid possibilities [11,15]. These issues are magnified in small-cohort, high-stakes programs such as CPC-level craft apprenticeships, where time is tightly constrained and both learners and trainers must prioritize activities that clearly contribute to examination success and employability.

Within this body of work, relatively few studies focus specifically on traditional crafts. Existing research tends either to address more industrial or technical domains (e.g. welding, machining, automotive) [13,16] or to examine crafts in museum or informal learning contexts rather than in formal VET programs[18]. As a result, we know comparatively little about how blended and hybrid designs function when cohorts are small, when the craft carries a strong cultural and identity dimension, and when national examinations impose rigid assessment frameworks. The Craeft glassblowing pilot contributes to this gap by examining a hybrid design in a real, high-stakes apprenticeship program with fewer than twenty apprentices per cohort, where experimentation must not compromise access to a recognized qualification [19].

2.4. VR and Immersive Technologies in Vocational Education

Finally, a growing literature investigates the use of VR and other immersive technologies in VET. Studies report benefits such as safe exposure to hazardous situations, the possibility of repeating rare or high-risk procedures, and increased motivation and engagement among learners [20,21]. For example, VR has been used to rehearse emergency responses, operate complex machinery, or practice procedural tasks in domains ranging from construction safety to healthcare and aviation [22,23]. These studies often highlight VR’s capacity to provide controlled, repeatable scenarios that would be difficult or expensive to stage in real settings.

At the same time, recent work drawing on CLT and eye-tracking/EEG methods has documented that immersive environments can also introduce additional cognitive load, particularly when visual scenes are cluttered, when instructions are not well integrated into the environment, or when redundant textual and auditory information is presented simultaneously [9,24]. Some studies find redundancy and expertise-reversal effects in VR: novices may benefit from rich guidance and multimodal cues, whereas more experienced learners can be distracted or even hindered by the same features [9,24,25]. Moreover, several authors caution that VR rarely replaces physical training; rather, it functions most effectively as a complementary layer for orientation, procedural familiarization, or debriefing, especially when followed or preceded by real practice [20,23].

Within the domain of intangible cultural heritage and traditional crafts, research has explored VR and mixed reality for demonstration and documentation—for example, mixed-reality glassblowing demonstrations and virtual reconstructions of craft processes in museums [18]. These studies emphasize the potential of immersive media to convey aspects of gesture, rhythm, and spatial organization that are difficult to capture in text or static images, while also acknowledging that material feel and haptics remain out of reach for current consumer-grade systems [18,26]. The Craeft platform builds directly on this work, offering a VR glassblowing simulator and 3D demonstrators designed to record, visualize, and share craft gestures within and beyond training institutions.

Yet, there is still a lack of systematic, program-level evaluations of how such tools actually affect learning trajectories, assessment outcomes, and the everyday practices of apprentices and trainers in formal VET settings. Most existing craft-related VR studies involve short-term trials or public demonstrations, not multi-cluster interventions embedded in a two-year qualification program with a control group. By examining the reception and use of VR and e-learning tools across two phases of a full academic year, and by coupling quantitative assessment data with rich qualitative feedback, the present study seeks to address this methodological gap.

2.5. Summary: Positioning the Craeft Pilot

Taken together, these strands of research suggest that digital technologies in craft VET must be understood at the intersection of situated practice, cognitive constraints, and instructional design. Situated and embodied perspectives remind us that glassblowing apprenticeships are grounded in

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workshop communities and material engagement; CLT and multimedia research highlight the need to manage cognitive load and to avoid redundancy in e-learning and VR design; and blended-learning studies show that hybrid formats are beneficial only when digital and physical activities are carefully aligned with authentic tasks and assessments.

The Craeft glassblowing pilot contributes to this landscape by providing a mixed-methods examination of how an e-learning platform and a VR workshop simulator are appropriated within a small-cohort, high-stakes apprenticeship program, and by analyzing how different usage scenarios, from separated to hybrid modes, shape their perceived value and observable impact on learning outcomes. In doing so, it offers empirically grounded insights into the conditions under which digital tools can support, rather than undermine, the material and social foundations of craft learning.

3. Educational Program and Technical Infrastructure

3.1. Glassblowing Program and Digitalisation Context

The intervention took place within the second year of the glass and crystal art apprenticeship program at the Centre Européen de Recherches et de Formation aux Arts Verriers (CERFAV) in France. The program alternates periods of company-based apprenticeship with center-based “clusters” in which apprentices attend intensive sessions in the glassblowing workshop and complete cross-cutting subjects such as general technology, health, safety and environment (HSE), and technical drawing, leading to the Certificate of Professional Competence (CPC).

Within the Horizon Europe Craeft project, CERFAV served as a reference case for exploring how digital tools could be integrated into such a craft apprenticeship without displacing core workshop practice. The glassblowing Pilot 1 was designed “to measure the impact of digital tools on the learning process” and to test hybrid usage scenarios in which e-learning and Virtual Reality (VR) tools would complement, rather than replace, traditional instruction.

3.2. E-Learning Platform (CLT)

The first core component of the Craeft technical infrastructure was an e-learning platform linked to the Craeft Authoring Platform and the Craeft Studio ecosystem. The e-learning platform was designed to support the cross-cutting theoretical subjects of the CPC curriculum by providing structured online modules aligned with existing teaching sequences. Modules covered, among others, the workshop environment, machinery and equipment, hand tools, glass composition and operating temperatures, HSE principles, general technology topics, and technical drawing. Each module combined several types of resources: explanatory videos filmed in the workshop, interactive quizzes, diagrams and schematics, and downloadable documents, organized to accompany the progression towards the CPC examination. Learners could use the platform to review course content, prepare for formative tests, and revisit key safety and process information independently.

Technically, the platform was accessible through a standard web browser, allowing asynchronous access from various locations (“everywhere at anytime” in the terminology of the teaching kit), provided that a suitable device and internet connection were available. While both the Traditional (T) and Traditional Augmented (TA) groups had institutional access to computers and non-Craeft digital resources, only apprentices in the TA group were explicitly guided and encouraged to use the platform as part of scheduled activities during clusters and as a support for their self-directed working hours and personal projects.

The platform also provided trainers with facilities to create and manage quizzes and to track completion, which made it possible to compile formative assessment results for comparison between groups. As part of the teaching kit developed in Craeft, the platform was presented as one element. An exemplary course as implemented in the platform is presented in Figure 1.

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Fundamental glassblowing techniques

Course Objective

In this course the fundamental techniques of glassblowing will be defined followed with exemplary visuals from their application.

Introduction

Glassblowing, one of the world's oldest and most revered art forms, marries the elements of fire, craftsmanship, and artistic vision to create mesmerizing works of art and functional glassware. This age-old craft has captured the imaginations of artisans and art enthusiasts for centuries, serving as a testament to human ingenuity and creative expression.

At its core, glassblowing is a captivating blend of science and artistry, requiring not only an understanding of the unique properties of molten glass but also a deep connection with the medium. Glassblowers harness the power of heat to transform a humble gather of molten glass into intricate sculptures, delicate ornaments, and functional vessels.

Central to the art of glassblowing are a set of fundamental techniques, each a skillful dance between the artisan's hands and the ever molten material. These techniques have been honed over generations, passed down from master to apprentice, and have allowed artists to push the boundaries of what is possible with glass.

In the following sections, we will embark on a journey through the key glassblowing techniques, exploring the intricate processes, perceptual stimuli, safety considerations, and the cognitive complexities that the practitioner encounters during each phase. We will dive into the mesmerizing dance of gathering, blowing, marvering, blocking, shearing, punting, finishing, annealing, engraving, and color application.

Throughout this exploration, we'll discover how glassblowers rely on their senses and craftsmanship to create, how they perceive the interplay of temperature, viscosity, and movement in the molten glass, and how they merge scientific precision with artistic intuition. This harmonious blend of creativity and technique is what sets glassblowing apart as a unique and captivating art form.

Whether you are a seasoned glass artist, a curious observer, or an aspiring artisan, this journey through the world of glassblowing techniques offers a deeper understanding of the art's complexity and its profound connection between the artist and their craft. It is an invitation to appreciate the intricacies and the magic that occurs within the walls of the glassblower's studio, where raw material is transformed into timeless works of art.

Gathering

Gathering is the initial step in glassblowing. It involves heating a blowpipe or punty (a solid metal rod) and dipping it into the furnace to gather molten glass. The glassblower then rolls the gathered glass on a marver (a steel table) to shape and cool it.

Process: The gathering process begins with heating the end of the blowpipe or punty in the pipe warmer (in some workshops on the sill of the furnace) until it reaches around 500 °C (930 °F), so that the blowpipe does not melt. The glassblower carefully dips the heated end of the rod into the furnace, allowing the molten glass to adhere to it. The glassblower rotates the rod while removing it to create a symmetrical gather.

Use: Gathering is the foundation of most glassblowing projects. The initial gather forms the core of the glass object and can be built upon with subsequent gathers to achieve the desired size and volume.

Observations: While gathering, glassblowers should observe the thickness and viscosity of the molten glass. The glass should adhere evenly to the blowpipe or punty. Proper temperature control is crucial to ensure a smooth gathering without dripping or irregularities.

Cognitive Process: During the gathering phase, the glassblower is focused on the selection of the right amount of molten glass and monitoring its viscosity. This requires an understanding of the glass's behaviour at different temperatures.

Safety Considerations:

- Wear appropriate protective gear, including heat-resistant clothing (avoid synthetic clothing), safety glasses, and safety closed-toe shoes.
- Beware of radiant heat from the furnace and avoid accidental contact with hot surfaces.

Perceptual stimuli:

- **Visual Perception:** Glassblowers observe the colour and texture of the gathered glass, which provides cues about its temperature and consistency. They observe the glass on the axis.
- **Tactile Perception:** They feel the heat radiating from the molten glass, and they must handle the blowpipe or punty with care to prevent burns. They assess the weight to keep the rod balanced and the glass in line.

Blowing

After gathering, the glassblower uses their breath to blow air into the molten glass on the end of the blowpipe. This technique inflates the glass, allowing the artist to control its shape and size.

Process: After gathering, the glassblower blows gently into the blowpipe to introduce air into the gathered glass. This inflation process expands the glass and shapes it. The glassblower controls the amount of air blown to maintain the desired thickness and form.

Use: Blowing is crucial for creating hollow glass forms such as vases, bowls, and glass sculptures. By blowing into the gather, the glassblower can control the size and shape of the final piece.

Observations: During blowing, glassblowers should pay close attention to the expansion of the glass. They must monitor the pressure applied to the blowpipe to achieve the desired thickness and shape. It's essential to avoid over-inflating the glass, which can cause it to thin out too much. The blowing action is more often done after marving or blocking but not directly after the gathering.

Cognitive Process: The glassblower must gauge the appropriate amount of air to introduce into the molten glass. They use their breath to control the expansion, requiring a keen sense of timing and an understanding of how air pressure affects the glass's shape and thickness.

Safety Considerations:

- Use a blow hose or blowpipe with a mouthpiece to avoid direct contact between the mouth and the hot glass.
- Maintain proper distance from the hot glass to prevent burns.
- Be cautious of over-inflating the glass, which can lead to thinning and potential rupture.

Perceptual stimuli:

- **Visual Perception:** Glassblowers watch for the expansion and shape of the glass as they blow air into it. Visual cues help them control the thickness and form.
- **Auditory Perception:** They listen for subtle sounds like crackling or hissing, which indicate the glass's state and temperature.

Marvering

Marvering involves rolling the glass on a marver to shape and cool it. The marver can be used to create cylindrical or conical shapes and maintain symmetry.

Process: Marvering involves rolling the hot glass on a marver, which is a steel or graphite table. This process cools and shapes the glass, often elongating it into a cylindrical shape or creating a more uniform surface texture.

Use: Glassblowers use marvering to refine and shape the glass. It aids in maintaining symmetry and can be used to create straight, cylindrical forms.

Observations: When marvering, glassblowers should observe the glass's temperature and texture. The marver helps cool and shape the glass. Uniform pressure and rolling are crucial to create symmetrical forms without cracks or irregularities.

Cognitive Process: While marvering, the glassblower is considering the desired shape and texture of the glass. They make decisions about how to use the marver to achieve these objectives and maintain symmetry in the piece.

Safety Considerations:

- Use a marver table at a comfortable height to avoid strain or awkward positioning.

Perceptual stimuli:

- **Visual Perception:** Marvering involves observing the glass's contact with the marver and monitoring its texture and shape.
- **Tactile Perception:** The glassblower feels the resistance as the glass is rolled on the marver.

Blocking

A block, typically made of wood, is used to shape and cool the surface of the glass further. The glassblower rolls the hot glass on the block to achieve the desired form and texture.

Process: The glassblower rolls the hot glass on the block, which can have a specific profile, to shape the glass into the desired form.

Use: Blocking is particularly helpful for creating complex shapes and contours in the glass, including creating the fundamental form of the glass object.

Observations: During blowing, glassblowers should pay close attention to the expansion of the glass. They must monitor the pressure applied to the blowpipe and the area of glass in contact with the block to achieve the desired thickness and shape. It's essential to avoid over-inflating the glass, which can cause it to thin out too much.

Cognitive Process: When blocking, the glassblower visualises the final form and decides how the wooden block will aid in achieving it. They must make quick judgments about pressure, speed, and the orientation of the glass.

Safety Considerations:

- Be mindful of splinters from the wooden block, and inspect the block for wear and damage.
- Check that there are no cracks on the side of the handle that could create a jet of burning steam.

Perceptual stimuli:

- **Visual Perception:** Glassblowers visualise the final form and how the wooden block will help achieve it. They monitor the glass's interaction with the block.
- **Tactile Perception:** The glassblower feels the pressure and feedback when rolling the glass on the wooden block.

Shearing

Shears or specialised tools are used to cut or manipulate the glass while it's still hot. This technique is often used in the bringing glass process, for creating specific shapes or patterns within the glass.

Process: Shearing involves the use of specialised tools to cut or manipulate the glass while it's still hot. Tools like diamond shears, straight shears, or jacks are used to create specific shapes, patterns, or decorative elements within the glass.

Use: Shearing allows the glassblower to add details, create openings, or modify the form of the glass while it's still malleable. Also cutting a piece of glass from a puntil.

Observations: When using shears, glassblowers must carefully cut or manipulate the glass. It's important to observe the angle and pressure applied to create clean cuts or desired shapes within the glass.

Cognitive Process: The glassblower must assess the design and decide on the placement of shears or cutting tools. They also determine viscosity of glass, the precise angle and force needed for the cut to achieve the desired shape or pattern.

Safety Considerations:

- Use appropriate shearing tools and handle them carefully to prevent injuries.
- Maintain a clear workspace to avoid tripping hazards.

Perceptual stimuli:

- **Visual Perception:** The artist observes the glass design and carefully positions the shears for cutting or shaping and he observes the glass colour to evaluate the temperature and the viscosity.
- **Tactile Perception:** Glassblowers feel the resistance as they apply force with the shears to achieve clean cuts or shapes.

Punting

Punting is the process of transferring the glass vessel from the blowpipe to a punty. This allows the glassblower to work on the other end of the object while maintaining control over its shape and symmetry.

Process: Punting is the process of transferring the glass vessel from the blowpipe to a punty (a secondary rod). This is done by creating a small gather of glass on the end of the punty and attaching it to the bottom of the glass object. Once securely attached, the blowpipe is removed.

Use: Punting allows the glassblower to work on the open end of the object, such as the rim or opening, while the punty provides support and control.

Observations: During the punting process, glassblowers should ensure a secure attachment between the punty and the glass object. Observing the connection point and its stability is vital to prevent accidents or misalignment.

Cognitive Process: When punting, the glassblower calculates the ideal attachment point for the punty to maintain balance and control. They consider the weight distribution of the piece.

Safety Considerations:

- Ensure a secure attachment when transferring glass to the punty to prevent accidents.
- Maintain proper posture to avoid strain when working with the punty.

Perceptual stimuli:

- **Visual Perception:** Glassblowers must visually assess the attachment point between the punty and the glass object to ensure it's secure and balanced. He also visually assesses the temperature of the glass object and glass on the punty to ensure proper assembly between the glass object and the punty.
- **Tactile Perception:** They feel the glass's weight distribution on the punty.

Finishing

Finishing techniques can include reheating and shaping, adding details, and creating openings or rims on the glass object. Glassblowers use various tools and equipment, such as jacks and tweezers, for these refinements.

Process: The finishing stage involves reheating and shaping the glass as needed. Tools like jacks, tweezers, and wooden paddles are used for these refinements. Artists can also add specific details or handles during this stage.

Use: Finishing brings the glassblowing project to its final form. It ensures that the glass is aesthetically pleasing and meets the artist's vision.

Observations: In the finishing stage, glassblowers should closely watch the glass's temperature and shape as it's reheated and worked with tools. Precise adjustments, such as creating rims or handles, require attention to detail.

Cognitive Process: In the finishing phase, the glassblower visualises the final details and shape of the object. They make decisions on tool selection and technique to achieve their artistic vision.

Safety Considerations:

- Use tools like jacks and tweezers with care to avoid pinching or crushing the glass.
- Keep the workspace organised and free from clutter to reduce the risk of accidents.

Perceptual stimuli:

- **Visual Perception:** During finishing, the artist visualises the final details and shape, making decisions about tool selection and technique.
- **Tactile Perception:** Glassblowers feel the resistance and feedback when using tools like jacks or tweezers.

Annealing

Annealing is the controlled cooling of the glass object to room temperature in a kiln. This process is critical to relieve internal stresses in the glass and ensure its durability. Annealing prevents the glass from cracking or shattering due to thermal stress.

Process: Annealing is the controlled cooling of the glass object in a kiln. The glass object is detached from the blowpipe or the punty at temperature corresponding to its annealing point and then slowly cooled to room temperature. This process relieves internal stresses, making the glass more durable and less prone to cracking.

Use: Annealing is a critical step to ensure the glass remains stable and structurally sound. It prevents the glass from shattering due to thermal stress.

Observations: While annealing, glassblowers should carefully monitor the kiln's temperature and cooling rate. Positioning within the kiln is essential to ensure even and thorough annealing, which prevents stress fractures. It's also important in terms of production constraints to optimise the number of glass objects put in the kiln.

Cognitive Process: Annealing requires understanding the specific annealing point of the glass and determining the appropriate kiln temperature and cooling rate to relieve internal stresses. It also involves precise scheduling and time management.

Safety Considerations:

- Be cautious when loading and unloading the kiln to avoid contact with hot surfaces.
- Use protective gear when handling annealed glass, as it may still be warm.

Perceptual stimuli:

- **Visual Perception:** Glassblowers monitor the kiln's temperature and the glass's position within the kiln to ensure even and thorough annealing.
- **Tactile Perception:** They may check the temperature of annealed glass to ensure it's cool enough to handle.

Perceptual stimuli in glassblowing

Certainly, in addition to the cognitive processes, glassblowing also involves a deep connection with the material through perceptual stimuli. Glassblowers rely on their senses to interact with the molten glass. Here's an exploration of the perceptual stimuli provided by the material.

Visual Perception

Stimuli: The vibrant, translucent nature of molten glass provides a visually stimulating experience. Glassblowers observe the glass's colour, texture, and transparency, allowing them to monitor its temperature and consistency.

Tactile Perception

Stimuli: The tactile aspect of glassblowing involves the physical sensation of manipulating the hot glass. Glassblowers can feel the molten glass's temperature, viscosity, and weight through the blowpipe or punty. They use touch to gauge the glass's malleability.

Auditory Perception

Stimuli: Glassblowing produces distinctive sounds that provide valuable feedback. The glassblower listens for specific cues, such as the crackling of the glass when it's too cool, or the hissing sound when air is blown into the piece. These auditory signals help in monitoring the process.

Olfactory Perception

Stimuli: The glassblowing studio has a unique smell due to the materials and equipment used. Glassblowers can detect changes in the process by the distinct odours produced, such as the smell of burning wood when wooden blocks are used for shaping.

Thermal Perception

Stimuli: Glassblowers can sense the temperature of the glass through the heat radiating from it. They must adapt to the changing temperature as the glass cools and solidifies, avoiding burns while working with the hot material.

Kinesthetic Perception

Stimuli: Glassblowing involves precise movements, and glassblowers rely on their kinesthetic sense to control the tools and their own body position. This includes the sense of balance and muscle memory when transferring the glass to a punty for example.

Figure 1. Learning unit illustrating a craft technique using images and structured explanatory text.

3.3. VR Glassblowing Workshop Simulator

The second key component was a VR glassblowing workshop simulator, developed within Craeft to provide a virtual representation of the CERFAV hot shop (see Figure 2). The simulator allowed users to move through a three-dimensional reconstruction of the workshop, identify, name and get information on tools and machines, and perform a limited set of operations, with particular emphasis on the "Gathering" gesture at the furnace. Its purpose was to familiarize apprentices with the spatial organization of the workshop and to offer a low-risk environment for cognitive rehearsal of basic sequences before working with molten glass.

The simulator ran on a VR headset connected to a dedicated computer and was used in a classroom or lab space at CERFAV where other apprentices could observe on a projected screen while one user interacted with the system. Trainers and apprentices treated the VR simulator primarily as an orientation and demonstration tool, a way to "get an idea" of the workshop and operations, rather than as a substitute for hands-on glasswork.

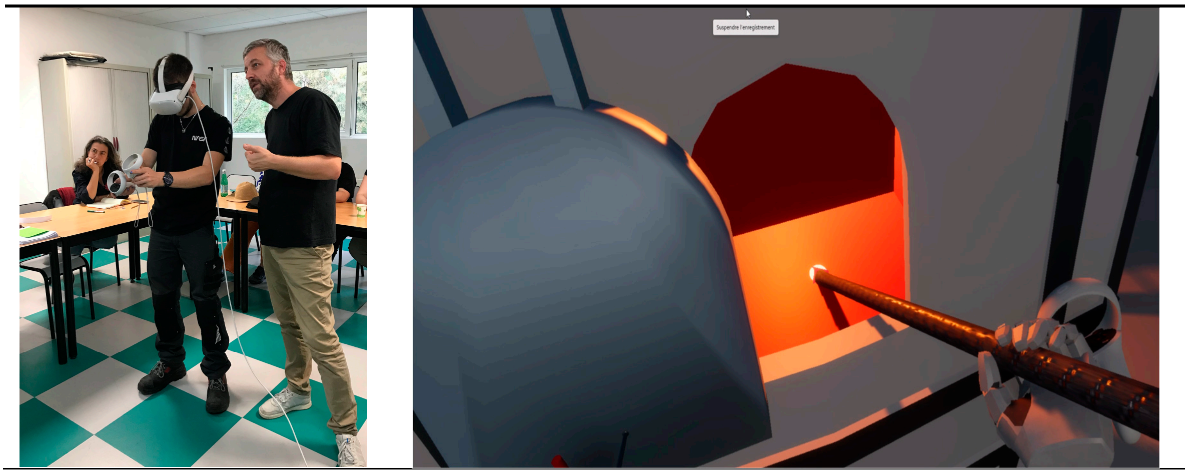

Figure 2. Screenshot of the Craeft VR glassblowing workshop simulator used at CERFAV.

4. Methodology

A central feature of the Craeft intervention was the design of hybrid usage scenarios that specified how the e-learning platform and the VR simulator would be combined with traditional teaching and workshop practice. Rather than simply adding digital tools on top of existing instruction, the teaching kit proposed an "ideal" model in which each tool had a defined role within a blended sequence of activities. This model distinguished three phases in the development of apprentices' personal projects: "I get informed", "I model", and "I practice" (see Figure 3).

In the "I get informed" phase, apprentices were expected to use the elearning platform to acquire or refresh theoretical knowledge on workshop safety, equipment, and processes, and to prepare for cross-cutting subject assessments. In "I model", they developed and refined the design and process of their individual glass pieces, sometimes using digital design tools (e.g. 3D modelling in the FabLab) in addition to sketches and physical mock-ups. Finally, in "I practice", they carried out the making phase in the workshop, which could be preceded by VR rehearsal of specific actions such as the furnace pick-up, depending on the availability of the simulator and the constraints of the timetable.

The digital tools modalities table (see Table 1) describes, for each Craeft tool, the typical location, time and synchronicity of use. For example, the e-learning platform was positioned as an asynchronous resource accessible "everywhere at any time", especially before and after workshop sessions, while the VR simulator was positioned as a synchronous tool used during workshop or project sessions, in the presence of a trainer. The table also indicated how the tools connect: the e-learning platform feeding into the apprentice studio and Craeft Studio for project documentation and evaluation, and the simulator feeding back into workshop practice through enhanced familiarity with equipment and procedures.

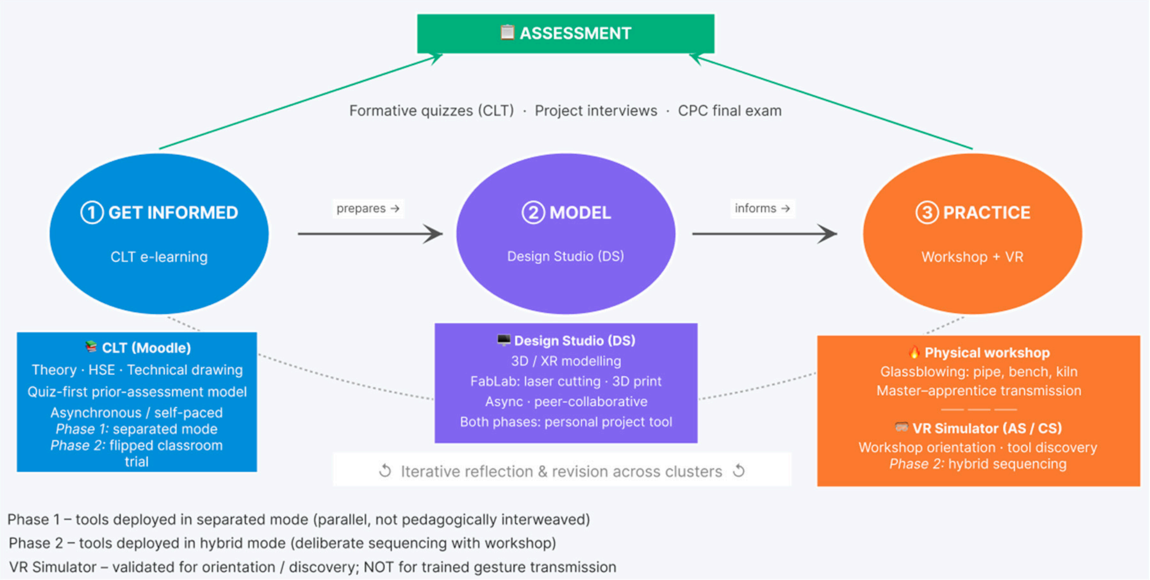

Figure 3. The "Get Informed – Model – Practice" hybrid learning cycle.

In the glassblowing Pilot 1, these usage scenarios were adapted to the constraints of the CERFAV program and the small group sizes. During pilot clusters, TA apprentices attended sessions that combined a reminder of the Craeft project, guided discovery and use of the digital tools, individual interviews on their personal projects, and workshop time. Over the course of the two phases, feedback from apprentices and trainers led to a shift from merely superimposing digital tools on existing teaching towards more integrated hybrid sequences; for example, using the e-learning platform systematically before specific assessments and aligning VR sessions more closely with upcoming workshop tasks. In this sense, the hybrid usage scenarios described here functioned both as a design blueprint and as a set of implementation hypotheses that were progressively refined between Phase 1 (separated deployment) and Phase 2 (integrated hybrid deployment).”

Table 1. Digital tools modalities.

Tool	Location	Time	Synchronicity	Phase 1 mode	Phase 2 mode	Main pedagogical role
E-learning platform	On-site or remote	Any time	Asynchronous (self-paced); synchronous when guided by trainer	Separated	Hybrid (incl. flipped classroom trial)	Theoretical knowledge acquisition; CPC exam preparation; formative self-assessment via quiz-first model
VR glassblowing workshop simulator	On-site (headset required)	Scheduled cluster sessions	Synchronous (supervised)	Separated	Separated (formal); Hybrid	Workshop orientation; tool and process discovery;

					(informal trial)	gesture visualization for novice learners
3D modelling tools	On-site (FabLab) or remote	Flexible	Asynchronous; peer-collaborative	Separated	Separated	Project design; form exploration; production planning
Video elicitation	On-site (workshop)	During or post-session	Synchronous or deferred review	Not included	Informal hybrid	Reflexive gesture analysis; tacit knowledge explication; trainer-led debriefing
Community portal	Remote	Any time	Asynchronous	Presented only	Presented + explored	Professional knowledge reference; peer exchange; craft community building
CERFAV's FabLab	On-site	Scheduled	Synchronous or asynchronous	Available to T + TA	Available to T + TA	Prototyping; laser cutting; 3D printing; production support

4.2. Research Design

This study employs a mixed-methods quasi-experimental design situated within an authentic glassblowing apprenticeship program. The design is informed by situated learning theory [1], which holds that craft knowledge is inseparable from the communities of practice and physical environments in which it is produced, and by cognitive load theory [6], which distinguishes between the explicit, propositional knowledge that digital tools can efficiently support, such as safety procedures, process sequences, and technical terminology and the tacit, embodied knowledge that remains anchored in direct workshop experience. This dual theoretical foundation guided both the structure of the digital learning intervention described in Section 3 and the selection of assessment instruments, which needed to capture theoretical learning outcomes as well as apprentices' perceptions of the material and practical dimensions of their training.

The study was implemented in two sequential phases at CERFAV over the 2024–2025 academic year. Participants were second-year apprentices preparing for their Certificate of Professional Competence (CPC), which they passed in June 2025. The apprenticeship takes place over two years, alternating between time spent in the company with the apprenticeship master and time spent in the training center, which we will call cluster. It is during some of these training center clusters that Pilot 1 was tested.

In Phase 1 (September 2024–January 2025), the Craeft digital tools were introduced across three center-based cluster periods (clusters 7, 8, and 9), with two to three two-hour sessions per cluster dedicated to the TA group, alongside individual project follow-up interviews conducted with

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apprentices from both groups. The primary aim of this phase was to measure initial tool reception and collect first formative assessment data for comparison between the T and TA groups. In Phase 2 (March–November 2025), the intervention was revised on the basis of Phase 1 feedback: hybrid usage scenarios were redesigned to more tightly interweave digital and workshop activities, and additional data were gathered through a further round of formal assessment comparisons, project follow-up interviews, an informal video elicitation experiment, and structured trainer debriefings .

4.3. Participants

Participants were second-year apprentices enrolled in the Certificate of Professional Competence (CPC) in glass and crystal art at CERFAV, preparing for the final examination in June 2025. All had completed a first year of alternating company-based and centre-based training before entering the study. At the project presentation session held at the end of their first year (June 2024), the full cohort was informed of the Craeft experiment and invited to volunteer for one of two conditions on a self-selection basis. Random assignment was not feasible given institutional constraints and the characteristically small cohort sizes of specialized craft apprenticeship programs in France, where centres such as CERFAV operate with annual cohorts typically numbering fewer than twenty apprentices per specialization [19,27].

The resulting participant groups are summarized in Table 2. In Phase 1, 17 apprentices took part in the project follow-up interviews: 5 in the Traditional Augmented (TA) group and 12 in the Traditional (T) group, with attendance varying slightly across clusters due to absences. In Phase 2, the groups were reconstituted with the incoming second-year cohort: 12 apprentices in the TA group and 7 in the T group. For quantitative comparisons of CPC examination results, only those apprentices who sat all relevant exam components were included in the analysis. A group of CERFAV glassblowing trainers additionally participated in a dedicated VR simulator trial in September 2025 followed by individual semi-structured interviews, constituting a distinct qualitative data source on the practitioner perspective.

Table 2. Participant overview by phase and group.

Phase	Period	TA group (*n*)	T group (*n*)	Total (*n*)	Data collected
Phase 1	Sept 2024–Jan 2025	5	12	17	Formative assessments, CPC exam, qualitative feedback
Phase 2	Mar–Nov 2025	12	7	19	Formative assessments, qualitative feedback, trainer interviews

4.4. Data Collection

Data collection combined quantitative and qualitative instruments to address the three research questions from complementary angles. Table 3 provides a summary of all instruments, the groups to which each was administered, and its primary analytical function.

Table 3. Overview of data collection instruments.

Instrument	Group	Type	Primary function
Formative assessments (General Technology, HSE, Technical Drawing)	T + TA	Quantitative	Impact of e-learning platform on cross-cutting theoretical learning
CPC examination results (4 components)	T + TA	Quantitative	Summative learning outcomes at end of program
Self-assessment questionnaire (e-learning and VR)	TA only	Mixed	Perceived mastery and usability of tools

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Satisfaction survey (e-learning and VR)	TA only	Mixed	Tool acceptance and improvement suggestions
On-the-spot feedback (presentation and tool trials)	TA only	Qualitative	First impressions, expectations, concerns
Personal project follow-up interviews	T + TA	Qualitative	Tool use in project work, relationship with material
Trainer VR trial debriefing and interviews	Trainers	Qualitative	Practitioner perspective on tool integration

4.4.1. Quantitative Instruments

Formative assessment scores in general technology, HSE, and technical drawing were compiled from marks recorded by subject trainers as part of regular curriculum evaluation and were not instruments specially designed for the study. They served as an observable indicator of whether access to the e-learning platform corresponded to any differences in theoretical performance between groups. CPC final examination marks were collected across four components: general technology, prevention–health–environment (PHE), making, and overall average, reported separately for the T and TA groups. Self-assessment and satisfaction questionnaires for both the e-learning platform and the VR simulator used Likert-type closed items measuring perceived ease of use, usefulness, and comfort, administered at the end of each cluster period for TA apprentices.

4.4.2. Qualitative Instruments

On-the-spot feedback was documented by trainers during plenary sessions and sub-group workshops at the initial project presentation and at subsequent tool sessions; contributions were organized under three axes — positive points, points for improvement, and open comments. Personal project follow-up interviews were conducted individually with all apprentices (T and TA) at each cluster using a structured interview guide (Annex 2) ; recordings were transcribed using noScribe v0.5 automated transcription software and anonymized by participant initials prior to coding. In Phase 2, a group of CERFAV trainers participated in a VR simulator trial followed by a recorded group discussion, and key subject trainers gave individual semi-structured interviews centered on perceived tool usefulness and integration with workshop instruction.

4.5. Data Analysis

Quantitative analysis. Given the small and structurally unbalanced group sizes which is a feature characteristic of specialized craft VET programs [19,27] all quantitative data were analyzed descriptively, following an approach that is well established in small-scale mixed-methods VET research . For each subject or CPC examination component, mean scores and standard deviations were calculated separately for the TA and T groups and compared. No inferential statistical tests were applied; the study itself acknowledges that the small participant numbers do not allow for definitive causal conclusions, and observed differences are therefore interpreted as indicative trends. Where relevant, the proportion of scores above threshold values (e.g. above 14/20) is reported to characterize distributional patterns beyond central tendency.

Qualitative analysis. Qualitative materials were analyzed using a thematic coding framework developed iteratively within the Craeft project and consistent with established procedures for reflexive thematic analysis in educational research [28]. The analysis proceeded in four stages: (1) transcription and organization of raw data into structured three-column tables (positive points / points for improvement / comments); (2) inductive identification of recurring themes through semantic grouping; (3) construction and systematic application of a stable coding scheme; and (4) frequency counting per code to establish the relative weight of each theme within each dataset.

The coding framework comprised two thematic clusters. For digital tool evaluation (e-learning and VR simulator): Pedagogical and didactic effectiveness (PDE), Ergonomics and accessibility (ERA), Exhaustiveness of content (EXC), Linking theory and practice (LTP), Pedagogical engineering (PEN), Technical and professional fidelity (FIT), VR ergonomics (EVR), and Practical aspects and security (PAS). For apprentice project practices: Mixed and pragmatic use of tools (MXU), Relationship with the material (RTM), Opportunities and limitations of digital tools (OLD), Subcontracting of digital tasks (SCD), Learning to use digital tools (DTL), Complexity of digital tools (CDT), and Collaboration with peers (CWP). Initial coding was supported by AI-assisted text analysis (Claude and Mistral language models) and subsequently reviewed and corrected manually to ensure accuracy and full traceability to the source data.

4.6. Ethical Considerations

The study was conducted within the institutional framework of CERFAV and the Horizon Europe Craeft project (Grant Agreement No. 101094349). Participation in both conditions and in all data collection activities was voluntary; apprentices chose their group freely and could withdraw from any data collection procedure without consequence for their CPC training pathway or examination standing. All participant data were anonymized prior to analysis, with individuals identified only by coded initials in interview transcripts and by group-level aggregation in quantitative reporting. The intervention was designed on the explicit principle that no apprentice’s access to a full and nationally recognized CPC program would be compromised, and digital tools were introduced as supplements to, not replacements for, core workshop instruction.

5. Results

This section presents the findings from both phases of the glassblowing pilot experiment in four sub-sections: (5.1) initial reception at project presentation; (5.2) quantitative outcomes from formative assessments and the CPC final examination; (5.3) qualitative findings on apprentices’ perceptions and practices across all cluster periods; and (5.4) trainer perspectives on tool integration and the informal Phase 2 experiments. Results are reported in line with the descriptive analytical approach set out in Section 4 and are interpreted as indicative trends rather than confirmed causal effects.

5.1. Initial Reception: Project Presentation (June 2024)

The Craeft project and its digital tools were presented to the full apprentice cohort at the end of their first year (June 2024), prior to the start of the experiment. This session served both as an introduction and as a co-design moment, with apprentices invited to contribute feedback on expectations, concerns, and proposals through a structured sub-group workshop.

Reception was intellectually engaged but critically mixed. Apprentices raised substantive questions about the medium and long-term challenges of digitizing craft skills, the risk of being "dispossessed" of their trade knowledge, and the practical maturity of the tools being proposed. Specific observations included: skepticism about the VR workshop simulator from those with prior glassblowing experience (“Simulation too far removed from the reality of the workshop”); a demand for design tools directly linked to production rather than simulation; and a clear attachment to physical material practice as a professional identity marker. More constructive expectations centered on the e-learning platform as a reference portal for technical knowledge, and on the value of the project follow-up system for tracking individual development.

This baseline reception is significant for contextualizing subsequent findings: the apprentices entered the experiment not with technological enthusiasm but with a pragmatic and professionally grounded evaluative stance, asking of each tool: ‘What’s it going to do for me?’ This orientation, demanding demonstrated utility over novelty, proved the most stable and consistent theme throughout the entire experiment.

5.2. Quantitative Outcomes: Formative Assessments and CPC Examination

5.2.1. Phase 1 Formative Assessments

The first quantitative comparison between the TA and T groups was conducted during cluster 7 (September 2024), using a formative assessment in general technology, a cross-cutting subject covered by the e-learning platform. The TA group (*n* = 4, one apprentice absent) recorded a mean score of 11.00/20 (SD = 6.63), compared with 10.18/20 (SD = 3.09) for the T group (*n* = 16). Whilst the TA group's mean was marginally higher, the substantially elevated standard deviation (more than twice that of the T group) indicated considerable internal variance within the test group. The highest mark in the TA group was 18/20 and the lowest 2/20, compared with 17/20 and 4/20 respectively for the T group, suggesting that access to the e-learning platform amplified learning divergence rather than producing uniform gains. The full-year mean results at cluster 10 consolidated this pattern across all three cross-cutting subjects, as shown in Table 4.

Table 4. Phase 1 year-mean formative assessment results by group.

Subject	T group mean (/20)	T group SD	TA group mean (/20)	TA group SD
General technology	10.94	2.61	11.00	6.63
Health, Safety & Environment (HSE)	11.94	3.10	11.40	6.06
Technical drawing	13.60	5.74	15.20	5.63

The TA group outperformed the T group in general technology (marginally) and technical drawing (notably: +1.60 points), whilst performing slightly below it in HSE. The technical drawing advantage is the most substantively interesting finding: technical drawing is the subject most directly supported by the design and modelling tools available within the e-learning platform, and the one where the content-tool alignment would be expected to produce the clearest benefit. In general technology and HSE, the TA group's standard deviation was at least twice that of the T group, a pattern interpreted as evidence that digital tools act as a *catalyst* and thus positively reinforcing outcomes for autonomous, digitally engaged learners whilst potentially leaving less motivated learners further behind. The study explicitly cautions that these findings are indicative only, given the small and unbalanced group sizes.

5.2.2. Phase 2 Formative Assessments

In Phase 2, the cluster 7 general technology formative assessment was conducted in October 2025 with the new second-year cohort (TA: *n* = 12; T: *n* = 7). The TA group recorded a mean of 15.33/20 (SD = 2.65), compared with 13.67/20 (SD = 2.73) for the T group and a full promotion mean of 14.24/20 (SD = 2.64). Three features of this Phase 2 result are analytically significant when set against Phase 1. First, the TA group's advantage over the T group (+1.66 points) was more consistent and credible than in Phase 1, sustained across a larger group. Second, and crucially, the standard deviations of the TA and T groups were now nearly identical (2.65 vs. 2.73), indicating that the divergence-amplification effect observed in Phase 1 had been substantially reduced. This convergence is attributed to the redesigned hybrid usage scenarios of Phase 2, which more deliberately integrated digital tool use with structured group activity, thereby supporting less autonomous learners more effectively. Third, the overall promotion mean (14.24) situated both groups within a credible performance range, lending greater contextual validity to the comparison.

5.2.3. CPC Final Examination Results

The CPC final examination results (June 2025) constitute the highest-stakes and most ecologically valid quantitative measure in the study, representing the nationally validated endpoint of the two-year glassblowing apprenticeship. The examination comprised four components analyzed in the study: general technology, Prevention Health Environment (PHE), making (practical), and overall CPC average. Results for the Phase 1 cohort are presented in Table 5, with figures calculated both including and excluding absent or partially-exempt candidates.

Table 5. CPC final examination results by group — Phase 1 cohort.

Component	T group mean	T group SD	TA group mean	TA group SD	Promotion mean (incl. absent)	Promotion mean (excl. absent)
General technology	14.71	2.78	13.00	2.32	13.81	14.36
PHE	13.85	1.89	17.00	1.41	14.50	14.50
Making (practical)	15,61	2,63	14,14	1,70	14,70	15,29
Overall CPC average	15.02	2.09	13.51	1.68	14.24	14.81

Ranges reflect computations with and without absent/partially exempt candidates.

The results present a differentiated picture across components. In general technology, the T group outperformed the TA group by 1.71 points (14.71 vs. 13.00), reversing the slight TA advantage seen in the Phase 1 formative assessments. In PHE, the result is strikingly different: the TA group outperformed the T group by 3.15 points (17.00 vs. 13.85), also with lower variance (SD = 1.41 vs. 1.89), with the TA group’s mean situating considerably above the promotion mean of 14.50. The PHE component covers health, safety, and environmental regulations — subject area covered in a consistent and comprehensive manner in the e-learning platform, suggesting that the platform’s targeted content advantage was realized most fully where the alignment between tool and curriculum objective was strongest. In the practical making component, the graph suggests no substantial difference between groups, though exact means are not reported separately. In the overall CPC average, the T group performed marginally better across both calculation methods (15.02–vs. 13.51).

The overall T group advantage is attributed to two compounding factors: the insufficiency of group sizes to support robust inferential conclusions; and, more critically, the shortcomings of the Phase 1 intervention e to achieve genuine integration of digital and traditional learning, having positioned the e-learning platform and VR simulator as added layers rather than genuinely interwoven components of the training scenario. This diagnosis — that tool superimposition is less effective than tool synergy — became the central design principle for the Phase 2 hybrid scenario redesign.

5.3. Qualitative Findings: Apprentices’ Perceptions of the Craeft Digital Tools

5.3.1. The e-Learning Platform — Phase 1

Cluster 7. The first systematic thematic analysis of e-learning platform feedback was conducted after cluster 7 (September–October 2024). The statistical analysis of feedback and satisfaction questionnaire data produced 71 coded occurrences distributed across four themes (Table 6).

Table 6. e-learning platform thematic analysis — Phase 1, cluster 7 (n = 71 coded occurrences).

Rank	Code	Theme	Occurrences	%
1	PDE-1	Quality of learning materials	18	25%
2	ERA-1	Navigation and interface	14	20%
3	PDE-2	Educational progress	11	15%
4	EXC-1	Core content completeness	9	13%
5	EXC-2	Specific technical aspects	5	7%
6	PDE-3	Assessment of learning	4	6%
6	ERA-2	Organisation of content	4	6%
8	ERA-3	Technical accessibility	2	3%

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8	LTP-1	Transfer of learning	2	3%
8	LTP-2	Professional contextualisation	2	3%

The dominant finding was strong appreciation for the quality and variety of learning materials, particularly the combination of instructional videos, quizzes with auto-correction, and interactive assessments: *'The questionnaires and explanatory videos are the site's best asset'* [PDE-1]; *'interactive videos, initial tests'* [PDE-1]. The 'quiz-first' model, which assessed prior knowledge before presenting new content, was specifically appreciated as a productive cognitive activation strategy. Navigation and interface issues constituted the second most prominent theme, with apprentices identifying the absence of breadcrumb navigation and difficulties in locating courses within the platform structure: *'No breadcrumb trail, no possibility of going back in the tree structure when you are in a course'* [ERA-1]; *'Quite complicated to find your way around the platform, I find it a bit scattered'* [ERA-2]. Content completeness generated significant feedback centered on gaps in technical drawing material and the excessive pace of certain instructional videos: *'In some courses there are things missing [technical drawing], there are gaps, a video is not enough to understand everything'* [EXC-1]. The theme of theory-practice linkage (LTP), whilst the least frequent in code count, was analytically the most conceptually significant: *'Making the link between the videos and the workshop'* [LTP-1] was articulated as an unmet but fundamental need, directly echoing the situated learning framework underpinning this study [1]. The usefulness of the e-learning platform for apprentices' personal projects was consistently rated as limited — not as a criticism of the tool, but as a correct recognition that the platform is a learning and revision tool, not a design or production tool.

Cluster 9. The cluster 9 analysis (January 2025) drew on 46 coded occurrences and showed both continuity and evolution relative to cluster 7. The quality of learning materials remained the dominant positive theme (14 occurrences, all positive), whilst navigation and content organization showed a more balanced profile — with both positive comments (*'The sessions are well organized'* [ERA-2]; *'It's very easy to find your way around the different courses'* [ERA-2]) and points for improvement (*'Organization not super clear if you don't know the site'* [ERA-1]; *'A bit hard to find your way around and know where to go at first'* [ERA-1]) — indicating iterative improvement had partially resolved the navigation issues raised at cluster 7. New feedback in the content exhaustiveness theme included requests for art history and glass culture modules (*'Add a general culture or art history section'* [EXC-3]) and criticism of technical video pacing (*'Video of the oval layout too fast, difficult to understand'* [EXC-2]). The assessment structure generated differentiated feedback: whilst auto-corrected quizzes remained appreciated (*'Quizzes + auto correction'* [PDE-3]), apprentices began requesting variation in question sets (*'The questions are always the same, it would be nice if they were given randomly'* [PDE-3]) and clarification of multi-answer quiz logic. The self-assessment questionnaire for cluster 9 showed stability in platform adoption relative to cluster 7, with improvements in account customization and consistent scores on navigation, interpreted as reflecting genuine familiarization.

5.3.2. The E-Learning Platform — Phase 2

In Phase 2 cluster 7 (October 2025), the TA group increased to 12 apprentices. Platform adoption presented no significant difficulties, with the main qualification being the need to understand the structural logic of a Moodle-based platform before autonomous use became fluent. Key findings from Phase 2 e-learning platform evaluation extended and confirmed Phase 1 results: the platform was valued as a discovery tool for other craft techniques beyond glassblowing (a capacity not explored in Phase 1), as a structured revision tool for transversal examination subjects, and as a repository of reference content. The HSE trainer's trial use of the e-learning platform for pre-session preparation demonstrated potential for a flipped classroom model, though the trainer acknowledged he had not yet received formal training in this pedagogical approach — a finding that points to the importance of trainer professional development as a condition for effective platform integration.

5.3.3. The VR Glassblowing Workshop Simulator — Phase 1

Cluster 7. Initial VR simulator feedback from cluster 7 produced 16 coded occurrences, with pedagogical engineering (PEN, 44%) and technical fidelity (FIT, 38%) emerging as the two dominant themes. The dominant sub-theme under PEN was learning structure (PEN-1, 25%), reflecting apprentices' requests for explicit task objectives and guided progression: *'Setting objectives (small tasks), e.g. making a glass drop'* [PEN-1]; *'Having tutorials — e.g. making a cup guided through the steps (process)'* [PEN-2]. Under technical fidelity, physical simulation and gesture reproduction were rated equally (FIT-1 and FIT-2, 19% each), with feedback centering on the simulator's inability to accurately reproduce glass viscosity behavior and the imprecision of hand controller inputs for pipe manipulation. Self-assessment questionnaire results showed that navigating the interface, using the Oculus headset, and appropriating the virtual environment were manageable for most TA apprentices, while the manipulation of virtual blowing tools received the lowest mastery ratings, attributed to the imprecision of tool grasping and the gap between virtual and real physics.

Cluster 9. By cluster 9, the VR simulator had received substantial technical updates between sessions. The cluster 9 statistical analysis drew on 69 coded occurrences across three themes, showing a marked shift in the feedback structure (Table 7).

Table 7. VR simulator thematic analysis — Phase 1, cluster 9 (n = 69 coded occurrences).

Code	Theme	Occurrences	Positive points	Points for improvement	Comments
PEN	Pedagogical engineering	20	12	7	1
PEN-1	Learning structure	5	1	4	0
PEN-2	Pedagogical objectives	15	11	3	1
FIT	Technical fidelity	25	3	18	4
FIT-1	Physical simulation	7	1	3	3
FIT-2	Reproduction of movements	8	0	8	0
FIT-3	Technical accuracy	10	2	7	1
EVR	VR ergonomics	24	7	15	2
EVR-1	User interface	21	7	13	1
EVR-2	3D navigation	1	0	1	0
EVR-3	Functionality accessibility	2	0	1	1

The most analytically significant finding in the cluster 9 data is the distribution of positive versus improvement-oriented feedback within the FIT theme: of 25 FIT occurrences, only 3 were positive, with 22 classified as points for improvement or comments. Most critically, the FIT-2 sub-theme (reproduction of movements) generated 8 occurrences, all without exception coded as points for improvement — the highest proportion of critical feedback of any single code across the entire dataset. Representative verbatim feedback illustrates the consistency and clarity of this finding: 'Be able to turn the cane with the left hand controller' [FIT-2]; 'The movements are not easy to manage' [FIT-2]; 'Real practice is better because you can feel them' [FIT-2]. The workshop tour and tool identification functions, by contrast, continued to receive positive feedback under PEN-2 (pedagogical objectives: 11 positive out of 15 occurrences): 'It's a good way to get an idea of what you're getting into before your first workshop experience' [PEN-2].

The cluster 9 data also confirmed a significant design tension around scaffolding: apprentices expressed strongly divergent preferences for guided versus free-exploration modes, with the most constructive suggestion pointing towards an adaptive model: 'A more guided scenario with levels of

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difficulty”; “Free access for those who already know and more guided access for beginners” [PEN-1]. The user interface (EVR-1) attracted both appreciation for spatial navigation and card-based tool information, and requests for more intuitive interaction design, improved information display, and the ability to physically interact with all tools in the virtual workshop.

5.3.4. The VR Glassblowing Workshop Simulator — Phase 2

In Phase 2 cluster 7 (October 2025), nine of eleven present TA apprentices completed the VR satisfaction survey. The analysis of 64 coded occurrences produced the following distribution (Table 8).

Table 8. VR simulator thematic analysis — Phase 2, cluster 7 (n = 64 coded occurrences).

Code	Theme	Occurrences	%	**Rank**
PEN	Pedagogical engineering	29	45%	1
PEN-2	Pedagogical objectives	18	28%	1
PEN-1	Learning structure	11	17%	3
EVR	VR ergonomics	21	33%	2
EVR-1	User interface	15	23%	2
EVR-3	Organisation of space	4	6%	—
FIT	Technical fidelity	13	20%	3
FIT-2	Reproduction of movements	8	13%	4
FIT-1	Physical simulation	4	6%	—
PAS	Practical aspects and security	1	2%	—

The PEN-2 sub-theme (pedagogical objectives) emerged as the single most frequent code in the Phase 2 VR dataset (18 occurrences, 13 positive, 5 improvement-oriented), reflecting consolidated appreciation of the simulator’s value as a workshop orientation and process discovery tool: “I think so, what’s great are the little explanatory notes and the opportunity to experiment” [PEN-2]; “For someone who knows nothing about glassblowing, this may help them understand the principle” [PEN-2]. This finding, consistent with Phase 1, points to a clearly validated use case: the VR simulator as a pre-practical orientation and vocabulary-building tool for novice apprentices.

Critically, the gesture-learning application of the simulator remained clearly and unanimously rejected by experienced apprentices. The FIT-2 sub-theme (reproduction of movements) generated 8 occurrences, of which 7 were points for improvement — reproducing with remarkable consistency the Phase 1 cluster 9 result. Representative quotations from Phase 2 make the finding especially clear: “No, not really, gestures are difficult to reproduce in VR” [FIT-2]; “No, the app won’t tell us if we know anything, so if we’re not being monitored, it’s almost counterproductive” [FIT-2]; “It’s handy for tools but not at all for gestures” [FIT-2]. In contrast, one positive response (“Yes” [FIT-2]) came from a non-glassblowing apprentice within the TA group (a stained glass specialist), consistent with the interpretation that the simulator’s gesture-learning value is primarily relevant to those who lack prior embodied workshop experience.

The EVR-1 sub-theme (user interface) showed a globally positive profile (15 occurrences: 11 positive, 2 improvements, 2 comments), with appreciation for spatial navigation and tool information cards offset by requests for greater graphical fidelity and more physical interaction supports: “More developed graphics and more physical supports (cane simulator with sensors)” [EVR-1]; “Complex to get to grips with at first and then you understand it relatively well as you go along” [EVR-1]. The adaptive scaffolding demand from Phase 1 was explicitly reproduced in Phase 2: “Guided for beginners, but more freedom for those who are already experienced” [PEN-1].

During Phase 2 cluster 8, the most recent version of the VR simulator was tested only with the glassblowing sub-group of the TA group (4 of 6 glassblowers present), following technical improvements by the simulator development partner. The main findings from the follow-up interview confirmed the cluster 7 pattern: general appreciation for the discovery and workshop-orientation function; specific recognition of the tool’s value for people with no prior contact with fire or workshop environments; and continued clear identification of sensorial feedback limitation and physics imprecision as barriers to using the simulator for trained gesture acquisition.

5.3.5. Apprentices’ Digital Tool Practices: Project Follow-Up Themes Across All Clusters

The project follow-up interviews, conducted with both TA and T apprentices at each cluster period across both phases, constitute the richest longitudinal qualitative dataset in the study. Taken together across all cluster periods, they produce a highly consistent thematic portrait of how glassblowing apprentices relate to, integrate, and evaluate digital tools in their professional practice.

Cluster 8 - Phase 1. The three dominant themes were: Mixed and pragmatic use [MXU] (TA: 8; T: 7 occurrences); Learning how to use digital tools [DTL] (TA: 5; T: 1); Relationship with the material [RTM] (TA: 1; T: 2). MXU’s dominance from the first follow-up cluster confirms that apprentices approach digital tools as part of an undifferentiated toolbox — using them, including Craeft tools, FabLab equipment, 3D printers, laser cutters, and parametric CAD — on the basis of task-specific utility rather than technological preference. Of the five TA apprentices, four planned to use a digital tool in their personal project, including VR organic modelling and parametric 3D modelling; notably, one apprentice had already finalized and committed her shape design through VR modelling. The DTL theme’s much higher occurrence in the TA group (5 vs. 1) reflects the additional learning curve introduced by Craeft-specific tool adoption — an expected but important finding for planning future integration.

Cluster 9 - Phase 1. The thematic structure shifted notably, with Opportunities and limitations of digital tools [OLD] becoming the dominant theme (TA: 12; T: 15 occurrences), alongside the appearance of Subcontracting [SCD] and Complexity [CDT] as significant themes (TA and T: 2 occurrences each). The emergence of SCD as a distinct pattern is analytically important: apprentices who needed 3D modelling for their projects, but lacked either the time or the motivation to master the tools themselves, systematically delegated this work to FabLab staff or digitally skilled peers. This behavior was observed in both T and TA groups and represents a pragmatic strategy for accessing digital capabilities without the cognitive investment in tool learning — a strategy that reveals the true cost of digital tool adoption in a craft VET context where workshop time is at a premium.

Cluster 10 - Phase 1. As the academic year neared completion and the CPC examination approached, the thematic profile broadened and diversified. Opportunities and limitations [OLD] and Collaboration with peers [CWP] emerged as co-dominant themes (TA and T: 4–5 occurrences each), followed equally by MXU, RTM, SCD, and DTL (3 occurrences each per group). The appearance of CWP as a major theme at this stage reflects an important finding: collaboration with technically skilled peers and FabLab experts became the primary mechanism through which apprentices resolved their encounters with digital complexity. This parallels the SCD pattern from cluster 9 but extends it: rather than pure subcontracting, apprentices at cluster 10 showed a more genuinely collaborative model of peer-assisted digital practice.

A corpus-level quantitative indicator further contextualizes these themes: across the full project follow-up transcripts (39,458 words), the word “digital” appeared 47 times, “computer” 27 times, “3D” 17 times, and “laser cutting” only 7 times. The low frequency of these terms relative to the total word count indicates that digital tools occupy a functional but entirely unremarkable position in apprentices’ professional vocabulary — present, useful, and integrated, but carrying no special technological weight or fascination in how apprentices describe their own practice.

Phase 2 cluster 7. In the larger Phase 2 cohort (n = 19), the project follow-up data confirmed and amplified all major trends from Phase 1. The three most frequent themes were MXU (TA: 13; T: 11), OLD (TA: 12; T: 15), and RTM (TA: 6; T: 6), followed by digital tool learning and subcontracting themes. The equal frequency of RTM across T and TA groups (6 vs. 6) is particularly significant: it confirms that the TA group’s relationship with material and physical practice was not diminished by digital tool exposure, and that attachment to the craft material is a shared professional value rather than a marker of digital resistance. Apprentices in Phase 2 articulated this clearly: the attachment to material is described as ‘a professional life choice’ not a rejection or ignorance of digital tools.

5.4. Phase 2 Informal Experiments and Trainer Perspectives

5.4.1. Video Elicitation

Video elicitation was introduced in Phase 2 as an informal additional experiment, outside the formal T/TA group comparison framework. More specifically Vermersch's methodology inspired our empirical video elicitation practices in the informal Phase 2 experiments, but we did not conduct explicitation interviews in the strict sense of his methodology [17]. Our process involved apprentices using first-person or GoPro camera footage of their own glassblowing gestures as a basis for structured reflective analysis, either individually or with a trainer. Whilst quantitative evaluation was not conducted, observational findings indicated strong potential: apprentices showed heightened engagement when reviewing their own technique, and trainers identified the approach as particularly valuable for making tacit gesture knowledge explicit and discussable without requiring simultaneous workshop practice. The key implementation challenge identified was the need for structured pedagogical guidance to lead video debriefing sessions effectively — without such guidance, video review risked becoming passive rather than analytically productive.

5.4.2. Hybrid Mode Experiment

A hybrid mode session was tested informally with *Créateurs Verriers* students (artistically oriented, not CPC apprentices) and with first-year apprentices, integrating e-learning platform modules, VR simulator sessions, and direct workshop practice within a single pedagogically sequenced learning scenario. The results, though qualitative, indicated that the combination of digital preparation and immediate physical practice produced a stronger sense of purpose and relevance for the digital components than either tool used in isolation — consistent with the original Phase 1 diagnosis that tool superimposition is structurally less effective than tool synergy. These informal findings directly informed the redesigned Phase 2 hybrid usage scenarios documented in the Educational Kit version 2.

5.4.3. Trainer Perspectives

In September 2025, a group of experienced CERFAV glassblowing trainers — representing profiles ranging from 50+ years of practice to younger practitioners participated in a group VR simulator trial followed by a recorded group discussion, and gave individual semi-structured interviews centered on tool integration and pedagogical impact.

Trainer perspectives converged on several key positions. On the VR simulator, all trainers recognized its legitimate value for pre-workshop orientation and vocabulary-building for complete beginners, and specifically for reducing anxiety among those intimidated by fire and industrial equipment. Experienced trainers described video review as ‘useful for analyzing errors (e.g. correcting cives) and accelerating learning’ whilst insisting that gesture transmission requires physical material presence as a non-negotiable condition. They also acknowledged the tool's interest but noted that its relevance diminished rapidly once apprentices had gained basic workshop familiarity. On the e-learning platform, the HSE trainer characterized it principally as a revision and engagement lever (a lever for engagement) with effectiveness depending entirely on the quality of trainer-guided hybridization. The platform's potential for a flipped classroom approach was noted but identified as requiring specific trainer training in the methodology before it could be implemented reliably.

Video elicitation, tested informally in Phase 2, was the tool that generated the strongest and most unanimously positive response from trainers, valued for enabling reflexive analysis of gestural practice and for creating a documentary record of apprentices' developmental trajectories. Its use was however conditional on structure: '*Its use must be targeted and structured to avoid digital overload and* *preserve human contact'*. All three trainers converged on the broader principle that digital tools require deliberate integration into pedagogical sequences — that provision of the tool itself, without accompanying scenario design and trainer professional development, is insufficient to produce learning impact.

5.4.4. Community Platform Reception

The Craeft community portal was presented to apprentices during Phase 2 cluster 7 and received positive reception as a concept, principally valued as a professional reference tool distinct from general social media platforms. Apprentices expressed interest in using it to identify and contact specialist craftspeople for technical advice, to discover other craft techniques, and to access a curated repository of trade knowledge. Specific improvement requests included: a higher proportion of video content relative to text articles; labelling of users by technical level (trainee, self-taught, expert); multilingual accessibility; and moderation controls. The tool’s credibility relative to general social networks was cited as a significant attraction. Apprentices described it as ‘more reassuring than other all-comers social networks’suggesting an unmet need for a trusted professional community infrastructure within the craft trades.

6. Discussion

This section interprets the findings of the Craeft glassblowing Pilot 1 in light of the theoretical framework outlined in Section 2 and the existing literature on craft VET, blended learning, and immersive technologies. It is organized around the three research questions: (1) how apprentices appropriate e-learning and VR tools within a hybrid design; (2) what differences in learning outcomes emerge between TA and T groups; and (3) how apprentices and trainers negotiate tensions between digital tools and material practice. It then discusses implications for craft VET design, limitations, and directions for future research.

6.1. Appropriation of E-Learning and VR Within a Hybrid Design

The first research question concerned how second-year glassblowing apprentices appropriate e-learning and VR tools when these are integrated into a hybrid training design during center-based clusters. The results show that apprentices engage with the e-learning platform and the VR simulator in distinct, tool-specific ways that are consistent across clusters and phases.

For the e-learning platform, thematic analyses across clusters 7 and 9 highlighted strong and consistent appreciation of pedagogical and didactic effectiveness (PDE), particularly the quality of learning materials and the quiz-first assessment structure. Apprentices described explanatory videos and quizzes with auto-correction as “the site’s best asset” and valued the way interactive elements supported revision and exam preparation, especially in General Technology and HSE. This pattern aligns with research showing that well-designed asynchronous modules can effectively support the acquisition and consolidation of propositional knowledge in VET, provided that the content is tightly aligned with assessment demands [11,13]. It also corroborates e-learning platform -informed work on the benefits of prior assessment and multimodal presentation when designed to minimize redundancy and focus attention on key task elements [6,7].

At the same time, apprentices repeatedly pointed to navigation issues (lack of breadcrumb trails, difficulty locating courses) and gaps in content (e.g. technical drawing, art history, glass culture), particularly in Phase 1. These comments mirror known challenges in blended learning implementations, where usability and information architecture can significantly influence perceived usefulness and sustained engagement [12,14]. Importantly, the e-learning platform was consistently perceived as a learning and revision tool, not a design tool; apprentices correctly did not expect it to support creative project development. This suggests that they developed a fairly precise mental model of the platform’s pedagogical role, which is a precondition for meaningful integration into their learning ecology [11].

The appropriation of the VR glassblowing simulator was more ambivalent but strikingly coherent. Across both phases, apprentices and trainers converged on a clear distinction between two roles:

- A positive role as an orientation and discovery tool for novices: getting an idea of the workshop layout, learning tool names, and demystifying the hot shop before first physical entry. This use case is consistent with prior work on VR in vocational settings, where immersive environments are most robustly supported for low-risk familiarization and procedural preview rather than fine-grained skill acquisition [20,22].
- A rejected role as a tool for gesture transmission for experienced apprentices. The FIT-2 code ("reproduction of movements") generated almost exclusively negative or improvement-oriented comments in both Phase 1 and Phase 2, with apprentices insisting that "real practice is better because you can feel" the material and that VR manipulation remained too imprecise for learning to turn the pipe or control glass behavior. This is entirely consistent with research on haptics and VR in manual skills training, which stresses that current consumer-grade systems do not provide sufficient force feedback or material fidelity for high-level motor learning in crafts and surgery [23,26].

From a e-learning platform and expertise-reversal perspective, these findings make sense: for novices with no workshop experience, VR reduces intrinsic load by providing a safe, visually rich, and low-stakes environment to build basic schemas about workspace organization and tool functions; but for apprentices already immersed in the workshop, the same VR environment becomes redundant and may add extraneous load because it cannot match the fidelity of real practice and provides no new information about gesture optimization [6,9,10,24]. The Craeft pilot thus empirically illustrates a phase-sensitive value of VR in craft VET: useful early as an orientation layer, of rapidly diminishing return once authentic material practice is underway.

The project follow-up interviews extend this picture by showing that apprentices adopt a pragmatic, mixed-use stance towards digital tools overall. They use whatever tool, Craeft, FabLab, or other institutional resources that serves current project needs, subcontract complex digital tasks when time or skills are lacking, and collaborate with technically stronger peers. This behavior resonates with studies of VET learners' technology use, which report that apprentices tend to integrate digital tools opportunistically and instrumentally rather than out of intrinsic technological enthusiasm [13,29]. In the Craeft case, this pragmatism is not a sign of resistance but a rational response to tight schedules and high assessment stakes: tools are appropriated insofar as they demonstrably help with exams, project execution, or professional identity building.

6.2. Learning Outcomes and the Role of Hybrid Design

The second research question asked what differences, if any, in learning outcomes emerge between the TA and T groups, and how these relate to the hybrid design. Here the results paint a nuanced but conceptually coherent picture.

In Phase 1, where digital tools were introduced mainly in separated mode (added on top of existing teaching without systematic integration), quantitative outcomes were mixed. In cluster 7 General Technology, the TA group achieved a slightly higher mean than the T group, but with much higher variance, suggesting that the e-learning platform use amplified performance differences rather than producing uniform benefits. Over the full year, the TA group outperformed the T group notably in Technical Drawing. This is a subject directly supported by the e-learning platform resources and design tools but not in General Technology or HSE, where differences were small or favored the T group. In the CPC exam, the TA group performed substantially better than the T group in PHE (where e-learning platform offers rich HSE resources), but worse in General Technology and overall average, with no clear advantage in the practical "making" component.

Given the small and unbalanced group sizes, these differences must be interpreted cautiously; the study explicitly refrains from causal claims and treats them as indicative trends only.

Nevertheless, the pattern is consistent with the argument that digital tools in separated mode tend to:

- Benefit already autonomous, digitally competent learners, who use e-learning platform strategically to reinforce their exam preparation (hence high performers in TA), and
- Provide little systematic support for less autonomous learners, who may not integrate e-learning platform use effectively into their study habits, thus widening dispersion [12].

This phenomenon resonates with concerns in blended learning research that adding online resources without reshaping overall course design can exacerbate inequalities in self-regulation and digital literacy [11,15]. It also confirms the Craeft team's own diagnosis at the end of Phase 1: tool superimposition is less effective than tool synergy, and digital resources must be assigned explicit roles in the learning sequence if they are to benefit the cohort as a whole.

In Phase 2, the redesign of hybrid usage scenarios appears to have mitigated this divergence and strengthened the contribution of digital tools to theoretical learning. It should be noted, however, that these patterns may also partly reflect profile differences between self-selected groups, and that Phase 2 constitutes an exploration with a distinct cohort (group) rather than a controlled replication (see limitations, section 6.5). In the cluster 7 General Technology assessment, the TA group obtained a higher mean with a standard deviation almost identical to that of the T group, suggesting that access to e-learning platform under a more structured hybrid design improved average performance without increasing dispersion. This shift is interpretable as the effect of:

- Systematic pre-session use of e-learning platform modules (a flipped classroom logic) for HSE and General Technology, reducing extraneous load during in-person teaching and focusing workshop time on application rather than exposition [6,11].
- Clearer timing of VR and e-learning platform in relation to assessment moments, making it more obvious to apprentices how digital activities feed into tangible outcomes.

Qualitative evidence supports this interpretation. Apprentices in Phase 2 continued to value e-learning platform for exam preparation and began to perceive it as a standard part of their learning repertoire rather than as an optional add-on; trainers experimented with assigning specific e-learning platform modules as preparatory homework, moving towards a flipped model for HSE despite acknowledging the need for more professional development in this pedagogy. Similarly, the VR simulator's role was more tightly framed as orientation and vocabulary-building for novices, avoiding the unrealistic expectation that it should improve gesture execution.

Taken together, these patterns support a central claim of the Craeft project and much of the blended-learning literature: the effectiveness of digital tools in VET depends less on their intrinsic qualities than on their orchestration within a coherent hybrid design [11,13]. When e-learning platform and VR were used in separated mode, benefits were uneven and sometimes accompanied by increased variance; once their functions were clarified and sequenced relative to workshop practice and assessments, tools began to play more consistent supportive roles, especially for theoretical and orientation-related aspects of learning.

6.3. Negotiating Digitalisation and Material Attachment

The third research question concerned how apprentices and trainers negotiate the tension between the introduction of digital tools and a strong attachment to material, workshop-based learning. Here the Craeft data offer a rich, longitudinal perspective.

From the outset, apprentices expressed *critical interest** rather than straightforward enthusiasm: they were curious about digital tools but asked tough questions about the "digitisation of craft skills", the risk of being "dispossessed", and the maturity and usefulness of the proposed tools. This stance matches broader observations in craft VET that digital innovations are evaluated through the lens of professional identity and legitimacy, not merely usability [2,5]. It is also consistent with situated learning accounts in which membership of a community of practice is defined by shared engagement in authentic tasks and by mastery of historically valued ways of working [1].

Across both phases, qualitative data show that neither e-learning platform nor VR weakened apprentices' attachment to material practice. On the contrary, the RTM code (relationship with the material) appeared with equal frequency in T and TA groups, emphasizing that for all learners, "being in touch with the material" and "working with fire and glass" remained central to their choice of profession and their sense of learning. Digital tools were accepted insofar as they supported this trajectory—for example by helping with exam success, by allowing safer orientation before entering the hot shop, or by enabling more ambitious project designs via the FabLab—but they were never viewed as replacements for the workshop.

Trainers shared and reinforced this position. Experienced glassblowers recognized the potential of VR and video elicitation for analysis and reflection (reviewing cives, discussing errors, tracing progress over time) but insisted that gesture transmission requires physical material presence and cannot be outsourced to digital media. They also underlined the importance of avoiding "digital overload" and preserving human contact and workshop time, echoing e-learning platform's admonition to avoid adding extraneous tasks that do not contribute to germane load [6].

The phenomenon of subcontracting digital tasks further illustrates the negotiated nature of digitalization in this setting. Instead of all apprentices being expected to become proficient 3D modelers, those whose projects required complex digital fabrication often relied on FabLab staff or peer collaboration, effectively distributing digital labor in ways that preserved focus on the glassblowing core. This pattern can be interpreted as a pragmatic adaptation to the dual pressure of limited time and high stakes: the cohort collectively ensures that digital tools are used where they add visible value, without allowing them to dominate individual learning trajectories. It resonates with observations in other VET contexts that learners and instructors treat digital tools as shared resources within a community, rather than as strictly individual competencies to be mastered uniformly [13,30].

Overall, the Craeft pilot suggests that in small, identity-rich craft programs, digitalization is likely to be negotiated, selective, and conditional. Apprentices and trainers are willing to integrate e-learning and VR where these clearly support exam preparation, safety, or project ambition, but they will resist any move that appears to threaten the primacy of workshop experience or to dilute the embodied, communal aspects of craft learning. Far from being a barrier, this critical stance can be seen as a resource: it forces intervention designers to articulate more precisely what each digital tool is for and how it respects the integrity of the craft.

6.4. Implications for the Design of Digital Tools in Craft VET

Several implications for the design and implementation of digital tools in craft VET follow from these findings.

First, digital tools should be assigned explicit, differentiated roles within the learning sequence, rather than being introduced as generic add-ons. In the Craeft pilot, the digital tools modalities framework (Table 1) and the "Get informed – Model – Practice" cycle provided a useful blueprint: e-learning platform for theoretical knowledge and exam preparation in asynchronous mode; Design Studio and FabLab for project modelling; VR for orientation and tool discovery; video elicitation for reflective analysis of practice. This kind of role clarity reduces redundancy, helps manage cognitive load, and makes it easier for apprentices to understand why they are asked to use a given tool at a given moment [6,7].

Second, the study underscores the importance of trainer professional development and co-design. The most promising hybrid configurations in Phase 2—flipped e-learning platform use for HSE and General Technology, targeted VR sessions before workshop entry, structured video elicitation debriefings—emerged when trainers engaged actively with the tools and began to adapt them to their pedagogical style. However, trainers also reported a lack of formal training in flipped classroom methods and in orchestrating video-based reflection. This aligns with broader findings that teacher readiness is a major determinant of blended learning success and that instructional innovation often stalls when trainers are left to "figure it out" individually [12,15]. For craft VET, supporting trainers to design hybrid scenarios that respect workshop rhythms and assessment requirements appears essential.

Third, the results suggest that VR should be positioned carefully in craft programs. Its main comparative advantages lie in: (a) pre-exposure and desensitization to complex workshops; (b) vocabulary-building and tool identification; and (c) potentially, replay and visualization of recorded sequences for discussion. Research studies claim that VR can substitute for hands-on practice in transmitting complex gestures are not supported by the data and are unlikely to be credible to practitioners, given current limitations of haptic technology [23,26]. Designers and policymakers should therefore temper expectations and invest instead in making VR excel at what it does well, integrated into a broader hybrid design.

Finally, the Craeft pilot illustrates that small, high-stakes craft programs require modest but robust evaluation strategies. Descriptive statistics, complemented by rich qualitative feedback, can yield meaningful insights even when random assignment and large samples are impossible. For institutions and projects operating under similar constraints, the Craeft approach, combining formative assessments, exam data, thematic analysis of interviews, and iterative redesign of usage scenarios, offers a pragmatic model for evidence-informed innovation.

6.5. Limitations and Directions for Future Research

Several limitations of this study provide avenues for further work. The most obvious is the small and unbalanced sample size: with 5 TA and 12 T apprentices in Phase 1, and 12 TA and 7 T in Phase 2, statistical power is low and group differences must be treated as exploratory. Future research could pool data across multiple cohorts or RCIs, or adopt multi-site designs, to examine whether the patterns observed here generalize to other crafts and contexts [31].

Second, group assignment was based on self-selection rather than randomization, raising the possibility that more digitally motivated or confident apprentices volunteered for the TA group. Although qualitative data suggest that both groups shared similar values regarding material practice and overall attitudes towards digital tools, more systematic measures of digital literacy and motivation would help disentangle selection effects from intervention effects [32].

Third, while the study provides rich insight into apprentices' and trainers' perspectives, it focuses on a single institution and national context (CERFAV, France). Comparative research across different VET systems, with varying degrees of digitalization and different relationships between school-based and workplace learning, would enrich understanding of how institutional factors mediate hybrid design [5,15].

Lastly, several promising elements, most notably video elicitation and the Craeft community portal, were implemented only informally or at an exploratory stage in Phase 2. Dedicated design-based research cycles could systematically test and refine these components: for example, comparing different formats and timings of video debriefing sessions, or analyzing patterns of use and professional networking on the community portal over time [17,18].

Despite these limitations, the Craeft glassblowing pilot offers rare, longitudinal evidence on the integration of e-learning and VR in a traditional craft apprenticeship, and demonstrates that digital tools can support learning effectively when they are woven into carefully designed hybrid scenarios that respect the primacy of workshop practice and the situated nature of craft knowledge.

7. Conclusions

This study examined the integration of an e-learning platform and a VR glassblowing workshop simulator within a formal craft apprenticeship program, using a two-phase mixed-methods design that contrasted a Traditional Augmented (TA) group with access to Craeft tools and a Traditional (T) control group following the standard curriculum. Across both phases, apprentices appropriated the tools in differentiated ways: e-learning platform was consistently valued as a high-quality resource for theoretical learning and CPC exam preparation, while the VR simulator was recognized as a useful orientation and discovery tool for novices but rejected as a medium for transmitting fine motor gestures. Quantitative results suggested that, under separated deployment in Phase 1, digital tools had uneven and sometimes contradictory effects on assessment outcomes, whereas in Phase 2, when tools were embedded in deliberately designed hybrid scenarios, the TA group showed more consistent advantages in cross-cutting theoretical subjects without increased score dispersion.

These findings support the conclusion that in small, high-stakes craft VET programs, the effectiveness of digital tools depends less on their intrinsic features than on their pedagogical orchestration within hybrid learning designs. Simply superimposing e-learning platform and VR on existing teaching risks exacerbating differences in self-regulation and digital literacy; by contrast, assigning each tool a specific role in an iterative "get informed – model – practice" cycle, aligned with workshop practice and assessments, can enhance theoretical learning and workshop readiness while preserving the centrality of material engagement [6]. The study also shows that apprentices and trainers are willing to integrate digital tools when they clearly support exam success, safety, and project ambition, but maintain a strong, explicit attachment to the workshop as the primary site of craft learning—an attachment that should be treated as a design constraint rather than a barrier to innovation [1].

For policy and practice, the Craeft glassblowing pilot suggests three priorities. First, investment in digital infrastructure for craft VET should be matched by investment in trainer professional development and co-design capacity, enabling instructors to develop hybrid scenarios that respect program constraints and cognitive load principles [6]. Second, expectations regarding VR should be calibrated towards its demonstrated strengths—orientation, vocabulary building, and reflective analysis through video elicitation—rather than imagined as a replacement for hands-on practice in transmitting complex gestures [17]. Third, evaluation of digital interventions in craft VET should embrace realistic, small-N designs that combine descriptive quantitative indicators with rich qualitative feedback, allowing institutions to iteratively refine hybrid models in context. While the results are necessarily context-bound, they offer an empirically grounded framework for thinking about how e-learning and immersive tools can support, rather than undermine, the situated, embodied character of craft learning in glassblowing and beyond.

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Abbreviations

The following abbreviations are used in this manuscript:

CDT	Complexity of Digital Tools
CLT	Cognitive Load Theory
CWP	Collaboration with Peers

DTL	Learning to Use Digital Tools
ERA	Ergonomics and Accessibility
EVR	VR Ergonomics
EVR-1	User Interface
EVR-2	3D Navigation
EVR-3	Functionality/Accessibility – Organisation of Space
EXC	Exhaustiveness of Content
FIT	Technical and Professional Fidelity
FIT-1	Physical Simulation
FIT-2	Reproduction of Movements
FIT-3	Technical Accuracy
LTP	Linking Theory and Practice
MXU	Mixed and Pragmatic Use of Tools
OLD	Opportunities and Limitations of Digital Tools
PAS	Practical Aspects and Security
PDE	Pedagogical and Didactic Effectiveness
PEN	Pedagogical Engineering
PEN-1	Learning Structure
PEN-2	Pedagogical Objectives
RTM	Relationship with the Material
SCD	Subcontracting of Digital Tasks

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