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Case Studies

A roadmap for designing eXtended reality tools to teach unit operations in chemical engineering: Learning theories & shifting pedagogies

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ABSTRACT

This paper explores the impact of shifting from paper-based to eXtended Reality (XR) teaching tools and is informed by a design project that took place at the Chemical Engineering department at the Technical University of Denmark (DTU.CBE). The authors believe that, for operator training, teaching methods that leverage exploring, constructing and experiencing are superior to traditional teaching methods that rely heavily on conceptualising and rationalising. Cognitive load theory is used to focus this pedagogic discussion on memory. Thereafter, a neuroscience model called SULEX is employed to decompose memory into four related cognitive functions, Perception, Instinct, Reflection and Intuition, and for mapping our learning activities to Bloom's Taxonomy. Thereafter, another model is presented to illustrate a range of teaching discourses that can be consulted for designing XR tools for instructional purposes. For operator training, we have recommended spatial reasoning, affordance theory, distributed cognition and situated learning, among others. Finally the insights derived from the cognitive and instructional analysis will be illustrated in the presentation of several design features that were implemented as part of a Virtual Reality instructional design project at DTU.CBE.

1. Introduction

1.1. Background

Recent advances in eXtended Reality (hereafter referred to as XR) technologies have afforded the education sector new opportunities to develop teaching and learning materials in various modalities (Jensen & Konradsen, 2018). And in recent years, the regular lockdowns that have resulted from the COVID-19 pandemic have hastened an appetite for remote education solutions (Lenz, 2021; Peters et al., 2020). Regardless, XR is a relatively novel application in the classroom and laboratory of mainstream 3rd level institutions (Jensen & Konradsen, 2018). Moreover, literature reviews on the topic indicate that the number of VR learning products at Chemical Engineering departments is small, and that the number of studies that evaluate the pedagogic value of these tools is smaller still (Kumar et al., 2021). However, evaluations for XR products that arise in industries who have matured in their use of simulation technologies, such as aviation, health and the military, indicate that there is a potential value proposition for XR technologies in practice-based learning where, for example, it has been shown that flight training simulators can increase the rate of learning specific multi-tasking actions (Koglbauer, 2015).

In another paper related to this same project (Carberry et al., 2022a), the authors mapped the intended learning outcomes for the operator training courses offered at DTU.CBE to a set of general competencies. This facilitated the identification of three key areas of knowledge and skills development for undergraduate students:

- Developing familiarity with physical structures
- Performing basic operations
- Reporting on experiments

Thereafter, that study illustrated how various XR modalities could serve the development of these knowledge and skill areas. In this study, we will go one step further and consider what cognitive processes are utilised for learning as a direct response to this learning modality. Rather than comparing different XR options however, this study will draw a comparison between teaching and learning tools that can be described

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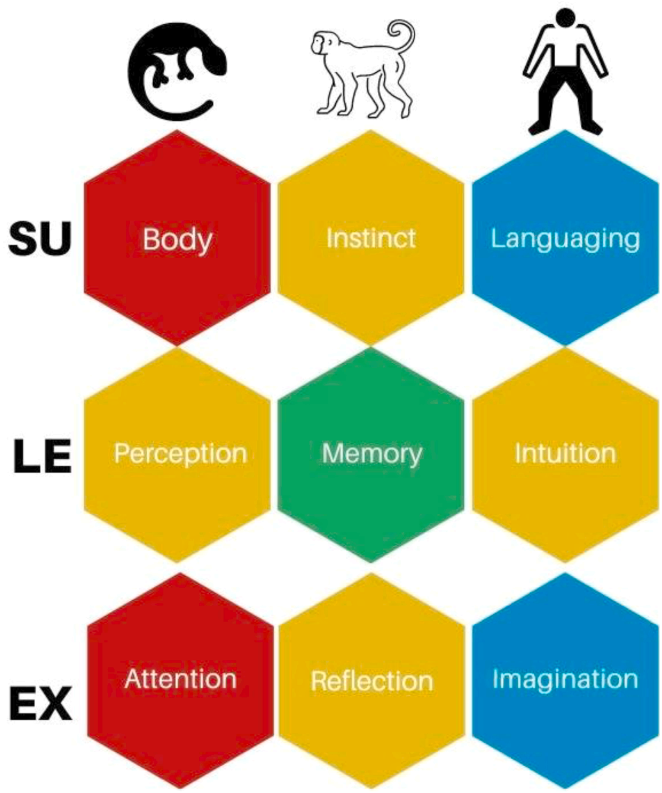

Fig. 1. The SULEX matrix.

as either traditional and non-digital, or, digitally-extended.

1.2. Cognitive load theory

Cognitive load theory was developed in 1994 by John Sweller and can be understood as the demand for attention placed on working memory. To understand why working memory is important in pedagogic design, one need only consider the average number of objects that a human brain can pay attention to simultaneously. Given a number of objects, and depending on the degree of interaction between them, i.e. if they are static and isolated or moving and interacting, this number is almost always seven or fewer (Sweller et al., 1988; Miller, 1956). In this study, cognitive load theory (hereafter referred to CLT) was employed as a theory to compare and analyse the difference between a hypothetical traditional teaching tool and a corresponding XR teaching tool.

Cognitive load is a useful concept for designing pedagogic materials because it is broken down into three facets: intrinsic load, extraneous load and germane load. Intrinsic load is the working memory required to meet the demands of the subject, extraneous load is the demand of the instructional medium, whilst germane load is the demand of knowledge creation (Sweller, 1994). CLT has many implications for designing pedagogical systems for both reducing extraneous cognitive load and moderating the attention of a learner for the purpose of accelerating knowledge acquisition.

1.3. Paper structure

This paper will proceed by introducing two cognitive models that were used in the development of one 360-VR learning tool for Pilot Plant training at CBE.KT. These models will present the concepts and introduce the education discourses that guided the design of the learning product. Thereafter, the paper will seek to illuminate how the pedagogic value of a learning tool can vary depending on its modality, and how the

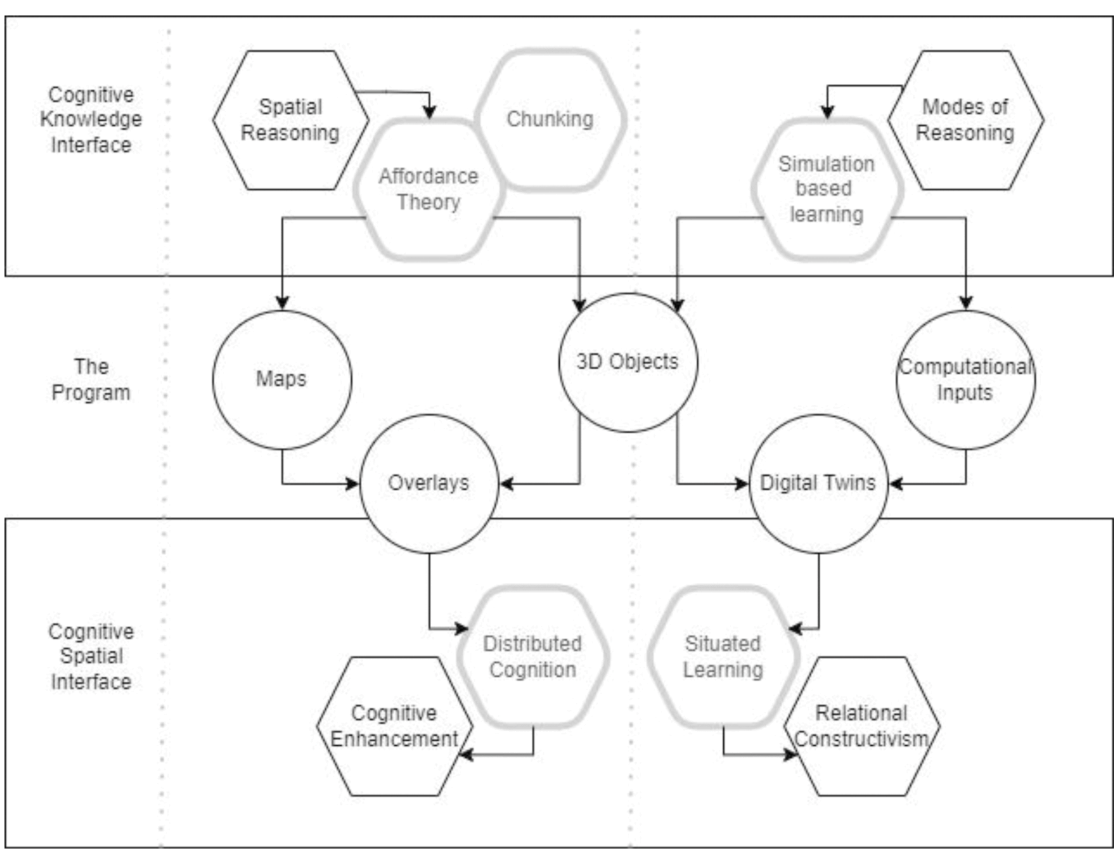

Fig. 2. The eXtended reality cognitive program (XR-C-P) model.

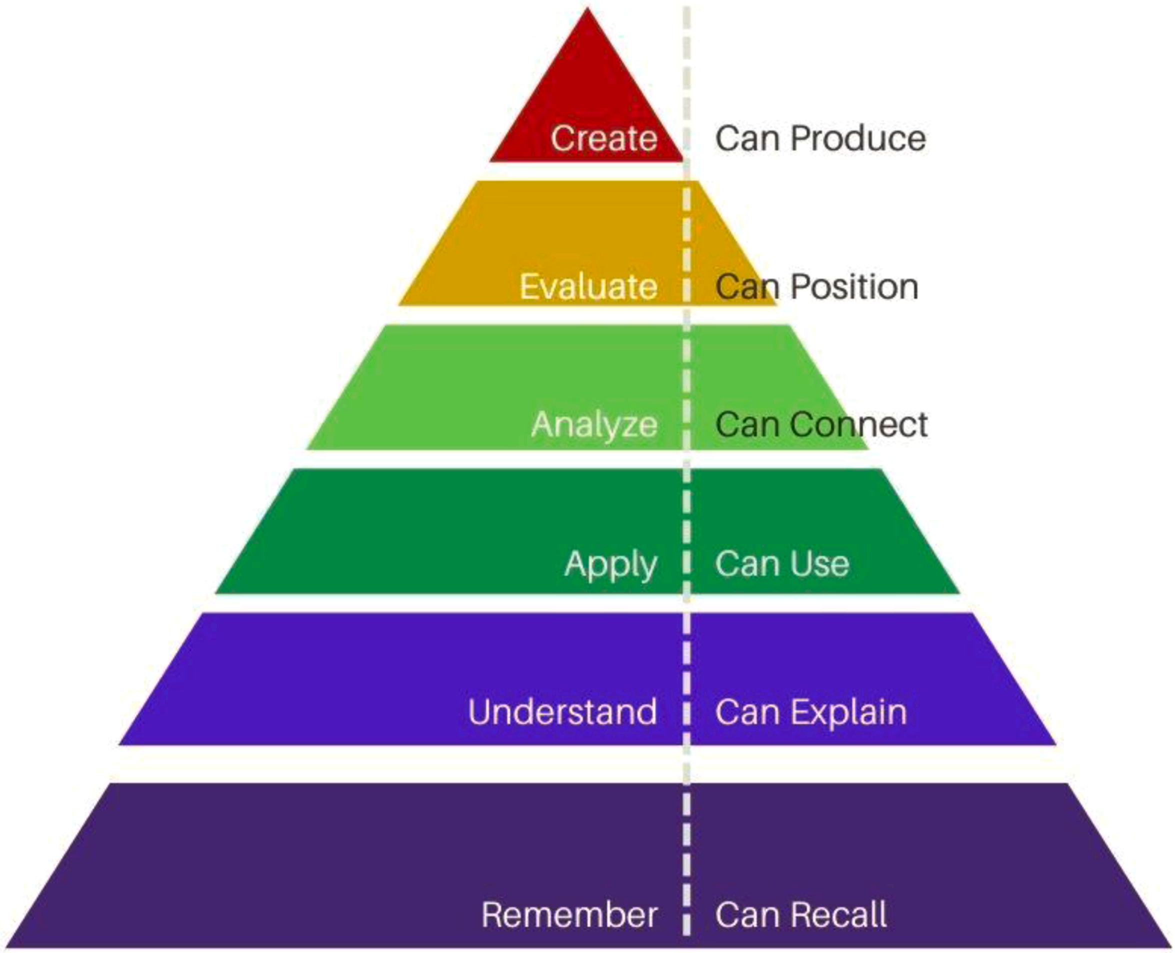

Fig. 3. Outline of Bloom's taxonomy.

effectiveness of that modality can elicit specific competencies. Finally, this paper will illustrate how these theories and models were applied to aspects of the design of the recently commissioned KemiTeknik 360-VR learning tool.

2. Models (material and methods)

2.1. Cognitive processes & SULEX

A cognitive process is the performance of some composite cognitive activity. The SULEX Matrix (Fig. 1) is a 3*3 cognitive framework that was originally developed by RoundPeg Republic Ltd. as part of a game that was intended to support professionals in understanding their own personal communication style. Later, it became useful as a framework for guiding the design of education and game-based products. The location of the different cognitive processes are located and related to one another in various ways. Columns are categorised as motifs; a lizard, a monkey and a human, and represent the evolutionary development of the human brain. Rows are categorised by labels; Survival, Learning and Experience/Expression, and represent functional purposes. This model was inspired by Paul MacLean's triune brain (Mac Lean, 1990) and a more detailed overview is available in Appendix 1.

A brief description of the categories in the model are as follows; Memory which is coloured green, occupies the central position in the matrix and indicates the central role that memory plays in cognition. Memory sits at the cross section of 4 other processes that are involved in memory production. Identifiable by their yellow colour, these are *Perception, Instinct, Intuition* and *Reflection*. In the two corners of the lizard column and coloured red, is *Body* and *Attention*. Body points to the relationship between the brain and physical movement whilst Attention points to the relationship between the brain and our sensory anatomy. Finally, in the two corners of the human column and coloured blue, are two combinatorial cognitive processes, *Languaging* and *Imagination*. The proximity of the categories to one another is also critical as it illustrates the strength of the connection between them. For example, *Body* is flanked by *Perception*, illustrating a more fundamental connection between moving and perception than say, moving and reflecting.

We will use this model later to explore the relationship between cognitive processes and learning mediums.

2.2. The XR-C-P model

Extended Reality options such as Virtual Reality (VR) and Augmented Reality (AR) are interfaces - mediums where the learner and the subject meet and interact. Earlier, we spoke about how extraneous load is the effort given to accessing a subject. It follows then that a digital interface, such as VR, is a source of extraneous cognitive load (Section 1.2). At the same time, this interface can moderate germane cognitive load by exploiting intuitive schemas.

The eXtended-Reality Cognitive Program model (Fig. 2), or XR-C-P model for short, is a model that was designed by the design team to support themselves and others in thinking about the value of eXtended Reality as an instructional interface. The SULEX framework and an online web resource titled learningdiscourses.com (Davis & Frances 2020) were utilised to support the development of the XR-C-P model. Learningdiscourses.com is a survey that provides an overview of several

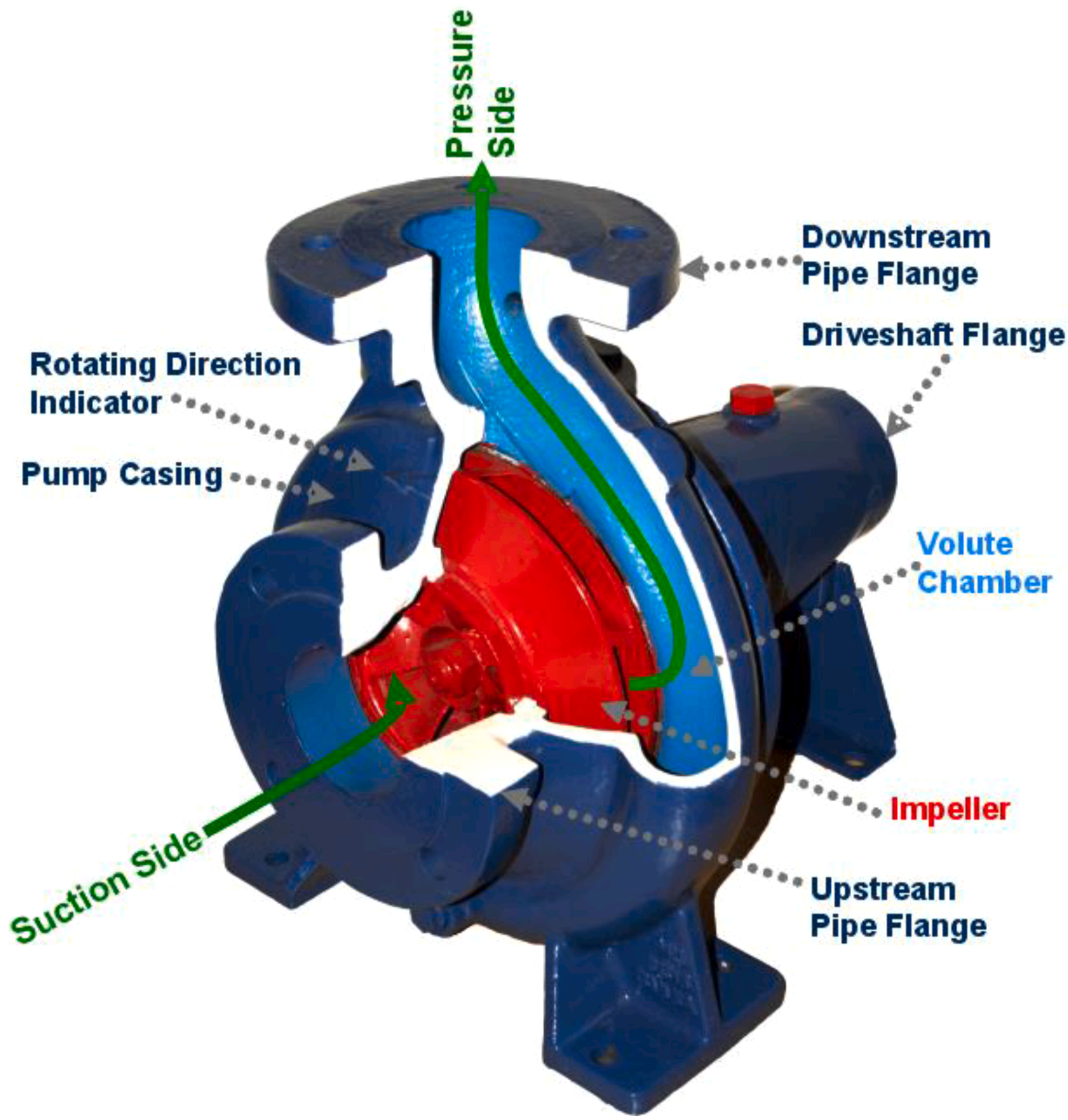

Fig. 4. 2D static image of a cross section of a centrifugal pump (Fantagu, 2008).

hundred learning discourses. Further, it categorises each discourse according to multiple criteria, making it relatively easy for a user to filter and select appropriate discourses for their own purposes. One of the ways these are categorised is according to whether a discourse influences or interprets learning. In our XR-C-P Model, discourses with a light soft-edged border *influence* learning whilst those with a darker blunt-edged border *interpret* learning. Bearing in mind that a learning tool is intended to influence learning, the discourses concerned with just that are valuable resources for shaping design features. However, for a deeper understanding about why these discourses are effective, or for employing a more innovative approach, discourses that interpret learning provide a body of knowledge to support developing original approaches.

The XR-C-P model is composed of 3 layers. The first concerns learning that is more consistent with the process of individual interpretation and is labelled the Cognitive Knowledge Interface. The second is a program layer that illustrates the assets and programs that constitute the instructional system. Finally, the third layer concerns learning which resides somewhat in the extended domain of space and place and is labelled the Cognitive Spatial Interface. Several educational discourses were evaluated for inclusion in XR-C-P. Of these, nine were selected. In contradiction to Davis and Francis classification however, we have opted to categorise Distributed Cognition as a discourse that influences learning as opposed to one that interprets it. The reason we have chosen to make this adjustment is because, in our products, we will be designing for the distribution of information.

Cutting the model in half along the central vertical axis, one can begin to observe two discrete sub-models that can be applied to two different instructional designs. The model to the left is for a mixed reality product that exploits spatial reasoning (Davis & Francis, 2022) for the design of affordances (Davis & Francis, 2022; Gibson, 1979) such as maps and 3D objects. In turn, these digital objects can be overlaid in an environment (real or virtual) where features that facilitate distributed cognition (Davis & Francis, 2022; Hutchins, 1991) can be exploited to enhance human cognition (Davis & Francis, 2022). Let's call this sub-model XR-C-P-Discover. The corresponding educational discourses are appropriate for body active learning.

Meanwhile, the model on the right side leverages simulations based on computationally driven 3D objects for a relational constructivist (Davis & Francis, 2022) understanding of a subject. Let's call this model XR-C-P-Simulation. These simulations, often referred to as digital twins, are suitable for situated learning (Davis & Francis, 2022; Lave &

Table 1
Which competencies can be served by what learning approaches, and their relationship to the SULEX model.

Learning activity	Conceptualise	Explore	Construct	Rationalise	Behave
Competency					
Familiarity with Apparatus		✓	✓		✓
Performing operations			✓		✓
Reporting on Experiments	✓			✓	
SULEX					
Motif	Human	Lizard	Lizard, Human	Human	Monkey
Memory traits	Intuition	Perception	Perception, Instinct, Intuition	Reflection	Instinct
Functional traits	Imagination	Body, Attention	Attention, Imagination, Body	Imagination, Languaging	Attention, Body

Wenger, 1991) that draws on various modes of reasoning (Davis & Francis, 2022).

The integration of simulation based technologies into XR teaching tools as described above has the potential to increase higher order learning according to Bloom's taxonomy (Fig. 3) (Vanderbilt University Centre for Teaching, 2016). And, in a highly interactive XR teaching product for example, it would be possible for students to make new or altered designs that impact the physics and chemistry of the corresponding simulated systems. In this instance it would become viable and straightforward to reach the *Create* level on Bloom's Taxonomy (Fig. 3), thus encouraging a mental state referred to as flow (Csikszentmihalyi, 1990). As flow results in an increase in focus and, assuming that greater focus increases germane load, we can expect student users of such tools to achieve a deeper level of learning.

3. Analysis

3.1. From 2D & 3D

In the section that follows, this paper will consider two hypothetical teaching aids in terms of their cognitive load profile: one paper-based and one digitally-extended. The goal for comparing paper-based and XR teaching tools is to illustrate the difference in cognitive focus between one and the other. This analysis is based on a thought experiment that was carried out by our design team. As a thought experiment, it required only the use of reason and therefore the assumptions that arise from the thought experiment are to be understood as logical inferences.

The thought experiment uses the three facets of cognitive load (Section 1.2) to articulate the difference between learning with a flat image (Fig. 4), and learning with a 3 dimensional virtual rendition of the same object (use your imagination here). Intrinsic load is the demand placed on working memory to understand a subject. In this case, the subject is the interior mechanism of a pump and is the same for both the 2D static image and the 3D dynamic object. On the other hand, extraneous load differs between the two teaching tools. In the case of the 2D static image, the learner can visually observe a cross-section of the internal mechanisms of the pump. To illustrate moving parts and, depending on the complexity of the mechanisms, either multiple images or symbolic elements may also be required to provide a learner with a fuller understanding of how the pump works. Using 2D static images then, a learner is required to conceptualise how the component operates using, to some extent, their imagination. Alternatively in the case of the 3D object, the learner could expect to interact with the model, probably by performing gestural commands that allow the learner to move, rotate and scale the component for a more involved investigation of its internal parts. And, if the object has been animated, it will be possible for the learner to observe the process through some 'play' command. In the 3D digital instance then, the learner is not required to imagine how the pump performs. Rather, they are encouraged to become knowledgeable about the inner workings of the component through the act of exploration.

Taking another example, if the learning tool is designed so that the intrinsic load is oriented towards being able to build a pump, then the extraneous load will also differ between the two instructional mediums. In this instance, the 2D static image might include a sequence of diagrams illustrating the order that one should build the component. Alternatively, in the case of the 3D dynamic object, the learner could expect to be able to take apart the (virtual) component and put it back together. As before, the nature of the extraneous load in the 2D instance arises from the need to conceptualise whilst the extraneous load in the 3D instance is oriented towards the act of constructing.

Taking a rather different example, we might look at methods for teaching learners about hazardous scenarios. In the traditional context, we might employ a case study and/or role play. A concern about the validity of role play as a method for teaching is whether a participant will behave in a real world setting similarly to the way they will behave in a role play. VR, however, can be quite effective at simulating real world scenarios that are task based. The effect of this is that we can shift the focus of germane load from *what I think I will do*, which is a rational perspective, to *what I will actually do*, which is behavioural.

In the context of the SULEX matrix (Section 2.1), conceptualising requires imagination which is supported by reflecting and intuiting. Alternatively, exploring and constructing are body focused activities that are mediated by the learner's perception and guided by their instincts. Body activated learning is a process of learning by being and doing. It is highly experiential and rooted in 'reality'. The word 'reality' in eXtended Reality denotes that the corresponding digital manifestations simulate reality. Therefore, and quite unlike the abstract-based mediums of traditional teaching aids, there is substantial potential in XR for representations that appeal to the senses, and incur visceral responses.

3.2. Linking cognitive processes to competencies

As stated earlier, developing Familiarity with physical structures, Performing basic operations, and, Reporting on experiments are the three critical competencies that arise from the intended learning objectives for the undergraduate courses on offer at DTU.CBE's PILOT PLANT (Carberry et al., 2022a, b). In this section, the cognitive processes identified in the last section will be considered in terms of their pedagogic value for each of these competencies.

Relatively speaking, the traditional learning activities that we have identified (conceptualising and rationalising) involve more thinking, whilst the XR enabled activities (exploring constructing and behaving) involve more doing. To offer a very simplistic illustration of the differences between thinking and doing in the context of these learning activities, conceptualising requires imagination and rationalising requires logic. Alternatively, exploring requires spatial awareness, constructing requires hand-eye coordination and behaviour (which is motivated and often unconscious) is perpetuated by experience.

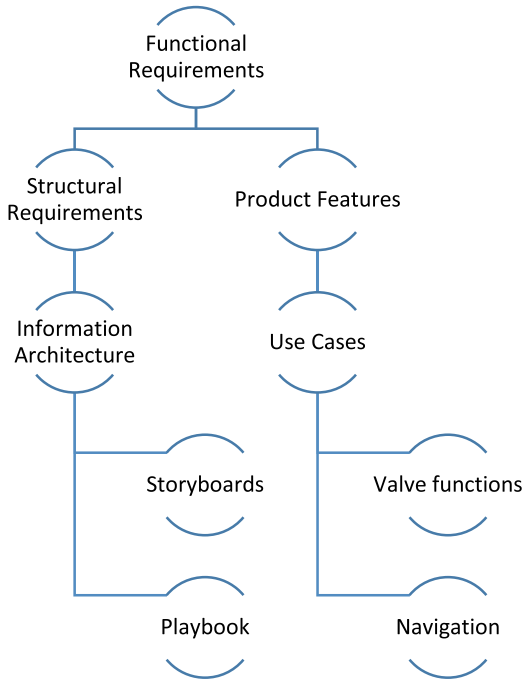

Fig. 5. Functional requirements overview.

It was beyond the scope of the KemiTeknik 360-VR project to conduct a deep analysis of these learning approaches and therefore it is beyond the scope of this paper to review these approaches in great detail. However, it would be remiss of the authors not to offer a literary starting point for each. A concept is an abstract idea and therefore conceptualising can be thought of as engaging mentally with these same ideas. A study for conceptualising can therefore begin with a reading of schema theory (Bartlett, 1932; Anderson et al., 1978). Exploring covers a wide array of activities from inquiring and examining to travelling. A study on learning discourses related to exploring physical systems (objects and landscapes) could begin with spatial reasoning (Gardner & Hatch, 1989). Constructing also covers a range of potential activities from building, making and forming. Here, the authors would recommend spatial reasoning, Enactivism (Varela et al., 1991) and Constructionism (Papert, 1980) as good entry points. Rationalism is the application of reason whilst reason is the action of applying logic. For theories about rationalism, the authors would recommend the $16^{th}/17^{th}$ Century philosopher Rene Descartes (Descartes, 1985) or the works of others who have studied Descartes in detail. For our purposes, behaviour is about actions and their underlying motivations. For theories on behaviour, we recommend both situated cognition discourses (Suchman, 1987) and B. F. Skinner's operant conditioning (Skinner, 1938). Despite the many critiques of operant conditioning (because it uses rewards and punishments to reinforce behaviour), it has good analogous power in situated learning contexts where the reward and punishments apply to simulated scenarios only.

Table 1 indicates which learning activities were deemed to have the greater benefit for what competencies. The design team believe that developing familiarity with unit operations and performing operations on same would be better served through *exploring* and *constructing* activities whilst reporting on experiments would be better served using *conceptual* and *rational* cognitive processes.

The table also highlights what cognitive processes (derived from the SULEX model (Section 2.1)) are applicable to each learning activity. Inspecting the table, we can instantly identify that *construct* requires a larger mix of cognitive functions to perform and may explain why it is located at the top of Bloom's taxonomy (Section 2.2)). To illustrate, when a learner shifts from 'conceptualising and rationalising' to 'exploring and constructing' for practical skills development (Table 1), they shift from Imagining and Languaging to Focusing (attention) Imagining and Moving. Taking the purpose of the learning into account, i.e. practical skills development, it can be observed that the general learning approach within Bloom's taxonomy for these learning goals will move up the pyramid. Hence, in this instance, we reason that educators can shift their learning goals from the more basic levels of *Understanding* and *Remembering* to higher levels such as *Creating* merely by switching their teaching modality and taking advantage of the technological benefits offered by Mixed Reality technologies.

Table 2
Illustrating the purpose, form and technologies for respective layers of a digital system.

Layer	Purpose	Form	Technology Examples
Back End	Data Storage and Design	Database, digital folders	SQL, MongoDB
Program	Operations	Programming	JavaScript, Python
Front End	Access	User Interface	Screen (Mobile, Tablet), Headset

4. Design study

Several digital reality products are under development at DTU.CBE. Some of these are intended for teaching and learning at undergraduate level whilst others are intended for research and learning at post graduate level. The design features for a 360 VR tool, of which this paper will provide a case study for, is intended for undergraduate education. Therefore, we will confine ourselves to the XR-C-P-Discover model hereafter.

4.1. Requirement specification

A requirement specification is an instructional manual for how to build a product. In the case of a digital product, it is broken down into two sections: Functional and Technical. In turn, the functional requirements can be broken down into several sections and can include instructions for information architectures and use cases. This paper will now document several of the functional requirements that were developed for the KemiTeknik 360-VR tool, as outlined in Fig. 5.

4.2. Information architecture

Information architectures are the structures by which information and content are organised, used and accessed. In a digital system we can think about information architectures in terms of source, functionality and access, which roughly equate to three layers of a digital system; the back-end, the program and the front-end, respectively. Table 2 illustrates the purpose, the potential form and some technology examples for each layer.

KemiTeknik 360-VR leverages an off the shelf production environment called present4D (Present4D Solutions UG (haftungsbeschränkt) i.G). Present4D is an interface for developing 360-VR media content and comes with a set of functions that eliminate the need for programming. As a result, the prototype did not require the project Team to invest in developing a program layer. For the same reasons, this 360-VR tool required only a set of well organised files and folders for the development of the back end. (This would not be the case for an immersive 3D game or a data driven simulator). In terms of the Information Architecture then, what was required was a menu design, a storyboard and a playbook.

The storyboards for the respective experiments that make up the KemiTeknik 360-VR suite were derived from the instruction manual for the same experiments, coupled with observations that were collected during actual experiments. Each step in the manual was, initially,

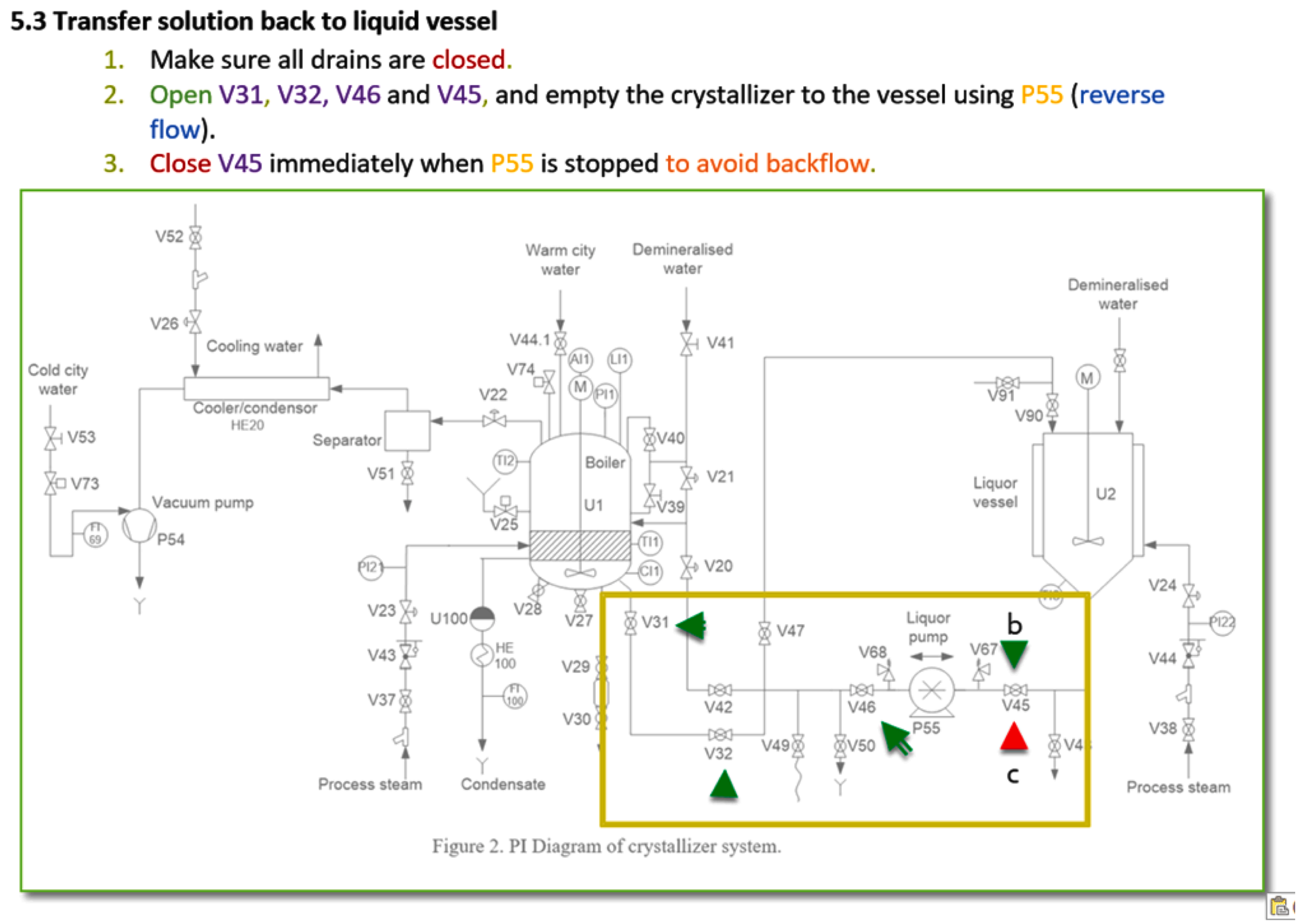

Fig. 6. Single legible scene, from storyboard for citric acid Crystalliser.

conceived of as a 'scene' in a larger narrative. Further, these scenes were also grouped together into modules when they were directed towards a common goal.

There was a method employed for the numbering and sequencing of the respective scenes where each scene is defined by two numbers. The first number indicates the module to which the scene belongs and the second number indicates the position of the scene in the overall order of events.

Fig. 6 depicts a specific step in the experiment, with information about the components involved and what one should do with them. The storyboard is an important design document for an animator. For the KemiTeknik 360-VR product, colour coding was employed to support the animator in identifying what actions needed to be performed on each component, and in what order. Here, red indicates stop (or off), green indicates start (or on), purple indicates that a component is a valve, green that it is a component other than a valve, blue that some annotation will be required, whilst orange indicates a potential safety issue. The storyboard also indicates the location of the components on a Piping and Instrumentation Diagram (PID) where colours and arrows are intended to speed up the animation workflow.

These storyboards were also used to guide filming of the process for each unit experiment (referred to hereafter as a walk-through). During the walk-throughs, the storyboards were often further annotated with information that was not available in the instruction manual. The storyboards, coupled with the video capture from the walk-throughs, served as the basis for the video and animation content that was produced as part of the final product. Further, some of the same features that were used to support the design workflow, such as the coloured arrows, also became product features in their own right, as these identifiers were deemed to be as useful to those learning how to perform unit operations as they were to the animators developing them.

A playbook is a set of rules that facilitates streamlining of a product design, with a view to creating consistency across the product. Examples of these rules include setting ranges for the length of titles and videos, setting word count targets, and, specifying when to use capital letters. KemiTeknik 360-VR employs a number of rules for each of Menu Titles, taglines, PID diagrams, Videos and Voiceovers, all with the intention of creating a more uniform user experience across the various modules and experiments.

4.3. Use cases

The requirement specification for the KemiTeknik 360-VR prototype consisted of several use cases. In this paper, two of these use cases will be illustrated. The goal in both cases is to reduce the amount of working memory required to interact with and learn about the physical unit operation and/or the KemiTeknik 360-VR interface. The first use case relates to the requirement for a learner to understand what it means when a valve position points one way or another (flow on, flow off, flow direction), whilst the second relates to the requirement for a user to be able to understand the experiment through the device of navigation. Following on from the development of the XR-C-P model, affordance theory was consulted to develop design features that would facilitate students in identifying correct valve positions, whilst chunking was employed in the navigation design to support sense-making. Relating these theories and methods to the SULEX model (Section 2.1),

Fig. 7. Screenshots of the 1st and 2nd iteration for valve positon affordances.

Fig. 8. Screenshot from the 'Watch Me First' Video, illustrating the interaction between valve position and solution flow.

affordances and chunking exploit perception and instinct. And, in terms of CLT, exploiting perception and instinct reduces the demand on working memory because existing mental schemas can be utilised, thus reducing the burden for creating new knowledge.

4.3.1. *Valves and affordances*

An affordance can be described as 'the quality or property of an object that defines its possible uses or makes clear how it can or should be used' (Merriam Webster Inc, 2022). Identifying when a valve is open or closed is very simple when you understand its relationship to the overall system. However, for someone in training on a unit operation it can be confusing, particularly with a three way valve that also moderates flow direction. At one of the early design review sessions, it was noted that the position of the valves in the product animations did not always correlate with the correct position in the experiment. After some deliberation, it was decided that it was important that the product should draw a learner's attention to the particular conditions that determine the position and corresponding function of a valve.

For the unit operations at DTU's PILOT PLANT, a valve is open when it is parallel to the piping on which it is located and closed when it is perpendicular. To illustrate this visually, several affordances were employed using symbols, colours and reference pipes, in an effort to illustrate the relationship between the valve position and the pipe. Fig. 7 illustrates the first and second iterations of this design feature which were implemented for a Citric Acid Crystallizer and a Fixed Bed Reactor Ion Exchange respectively. Further, the circular orange 'frame' became a device in its own right for communicating these supplementary affordances, and the design team continued to experiment with these features throughout the development of the second virtual unit operation experiment.

A Fixed Bed Reactor Ion Exchange was selected as the second unit operation to join the planned library of experiments. Here, the design team went further and developed a 'Watch Me First' animation to illustrate the interaction between valve position and flow direction. Further, symbols were now used extensively throughout the animations to augment the demos with information about the mechanics of the corresponding systems. Fig. 8 depicts a screenshot from the 60 s 'Watch Me First' video which is also provided as a separate media file in the

Fig. 9. Screenshot of the Menu page for the current implementation.

supporting documentation (file name: 11B_2.0).

4.3.2. *Navigation and chunking*

The design team conceived of three navigation categories for performing experiments on a unit operation, and by extension, for the KemiTeknik 360-VR experiment. The first relates to navigating the experimental steps, the second to navigating the structure and apparatus of a unit operation whilst the third occurs at the intersection between the

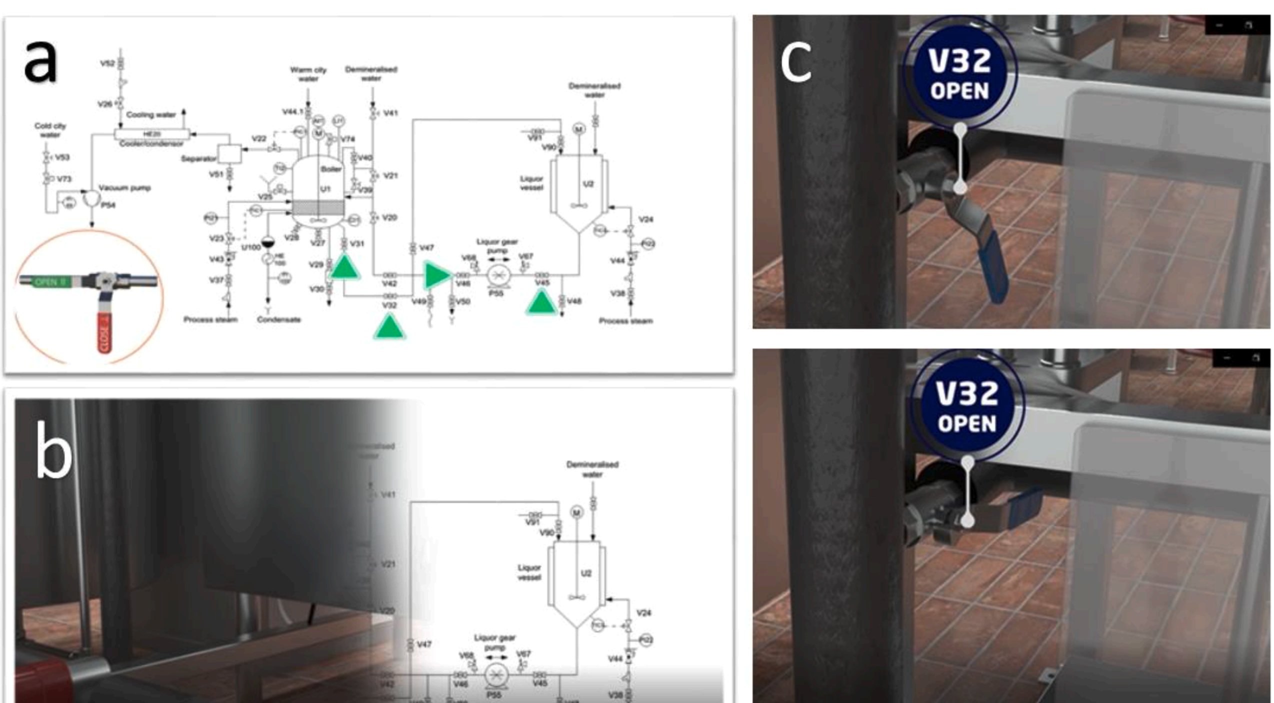

Fig. 10. Screenshots from Stage 5, Scene 3 of DTU.KT's virtual Citric Acid Crystallizer experiment.

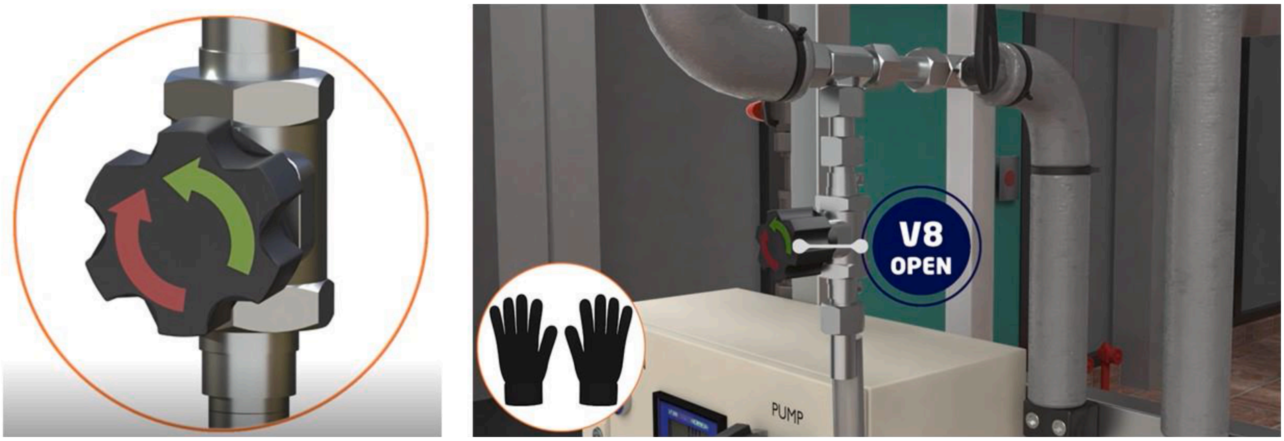

Fig. 11. Affordance frame indicates the need for gloves. Augmented valve indicates the rotation effect.

first two. In the case of navigating the experiment, and as per the Information Architecture, a menu and a set of nested menus were devised using the stages and sequences of the experiment. Fig. 9 illustrates the menu for the Citric Acid Crystallizer, demonstrating 5 experimental stages that roughly equate to *preparing, transferring, operating, testing* and *cleaning up*.

In the case of navigating the physical unit operation, this involves several distinct abilities that include locating the position of individual components, and, performing operations on them. However, fluency in carrying out experiments on unit operations is not achieved by an ability to follow a sequence of events or by an ability to locate and adjust components. One also needs to be able to comprehend the relationship between the components, both within and across the steps. Where is the experiment going?, when is it going there?, and, why? Hence, purpose and context are critical factors in the design of a feature that uses navigation as a device for sense-making.

Piping and Instrumentation diagrams (PID(s)) are symbolic systems for communicating and learning about the corresponding physical infrastructure of an experimental setup, typically for interconnection of chemical process equipment and the control thereof. As such, chemical and biochemical engineering students are introduced to them early in their undergraduate studies. One of the key features of KemiTeknik 360-VR is a sequenced catalogue of animations that collectively demonstrate an experiment, from start to finish. These animations leverage the PID as a schema to support learning about the corresponding physical unit operation, with the intention of reducing intrinsic load. This is achieved by using the PID as a navigation artefact. Here, the animations shift back and forth between an annotated PID and an animated demonstration of a virtual rendition of the physical lab space.

In its first iteration, the design of the KemiTeknik 360-VR tended to the first two navigation categories. It sought to order the experiment into a sequence of steps and demonstrate the position and operations for each component. In other words, the animations were developed so that a user would observe each experimental step one component change at a time. Then, during the first round of product reviews, it was noted that the experiments did nothing to explain the system or the process. Taking this feedback, the design team sought to improve the explanatory power of the animations. The solution resided in grouping the individual actions into meaningful chunks. In this second and current iteration for this feature, the user is presented with a PID that highlights several related components simultaneously before shifting to an animated demonstration of the corresponding chunked actions. Coupled with improvements in aural annotation, the second round of product reviews avoided the same criticism as the first.

Fig. 10 depicts several screenshots from the 80 s video for stage 5 (finishing) step 3 of the virtual Citric Acid Crystalliser unit operation experiment. 10(a) illustrates the chunking of several related single tasks into a single action, 10(b) expresses the shifting narrative between the PID and the video demos whilst 10(c) demonstrates the instructional tags that augment the video animations. This demo corresponds to the specific scene in the storyboard depicted in Fig. 6 (located in Section 4.2 Information Architecture), which is also provided as a separate media file in the supporting documentation for further illustration (file name: 9A_5.3).

5. Discussion and future work

This paper provides a model called XR-C-P to illustrate a range of education theories that can be consulted for XR development. We wish to point out that the learning discourses that were selected for inclusion in XR-C-P, whilst deemed appropriate by our design team, are by no means the only suitable educational discourses for an XR education framework. Therefore, whilst this model may serve as a good starting point for those who are new to education theories and/or XR technologies, the authors would encourage others to undertake their own assessment prior to commencing such projects.

In this project, the design team exploited a small number of opportunities that XR technologies can facilitate. For the most part, the current features of DTU’s KemiTeknik 360-VR support remote learning for single individuals. However, there is ample opportunity to develop functionality that promote collaboration among multiple users simultaneously. In future work, the design team would like to leverage these technologies for multiple users to support education theories such as Peer Instruction (Mazur, 1997) and to promote skills such as Teamwork.

6. Conclusion

Throughout this paper, the authors have sought to present a cohesive approach for incorporating education theories into instructional design whilst prioritising modalities that offer the most pedagogic value. Specifically, the authors present a thought experiment in order to identify which cognitive processes are elicited during learning for each of traditional paper-based and digitally-extended mediums. This experiment generated results that linked conceptualising and rationalising to traditional learning tools, and, exploring, constructing and experiencing to digitally-extended tools. Thereafter, a brief analysis was presented to consider which of these cognitive processes offers greater value for learning pilot-plant operations. Here, a competency framework that was generated from the intended learning outcomes for the corresponding courses provided a reference system to simplify a comparative study. This comparative study indicated that digitally-extended mediums were better suited for developing familiarity with and for performing basic operations, whilst traditional approaches would be better suited for developing reporting skills. Therefore, in the case of carrying out experiments at the PILOT PLANT at DTU.CBE at undergraduate level, the design team recommends prioritising digital reality tools with a view to improving pedagogic outcomes.

This paper set out a number of design methods that were applied in the design of KemiTeknik 360-VR that the authors would recommend to other teams who are new to and interested in pursuing similar goals. These methods include investing time in developing information architectures that make sense. Sorting, grouping, and structuring content will give an information system more shape and increase the ease at which users can learn how to navigate it, thus reducing cognitive load during its use as a learning aid. And, utilising a playbook will promote symmetry (consistency and cohesiveness) across product features which in turn will streamline expectations and improve user experience.

As a final note, and one that addresses continuous product improvement, the quality of the design in our second virtual unit operation was significantly better than the first. The affordance frame (orange circle) facilitated the systematization of affordances across the PID and the demos, whilst the content from the affordance frames could be easily leveraged to augment the animated demonstrations. This opportunity was only more fully realised in the second and subsequent offerings. Fig. 11 illustrates one such opportunity to use the affordance frame to visually communicate instructions, in this instance, when to wear gloves. In the same manner, one could use the affordance frame to communicate all levels of safety concerns throughout an experiment.

This paper documents a design study for one 360 VR product to improve teaching and learning about unit operations at the Chemical and Biochemical Engineering department at the Technical University of Denmark. Only commissioned in 2022, the value of the product as a pedagogic tool will be field tested in the near future, providing even more opportunities for product improvement. In the meantime, the initial student reactions are very positive and some are showcased in this product overview video (https://vimeo.com/user43544908).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.dche.2022.100074.

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