Immersive Process Model Exploration in Virtual Reality

André Zenner, Akhmajon Makhsadov, Sören Klingner, David Liebemann, and Antonio Krüger

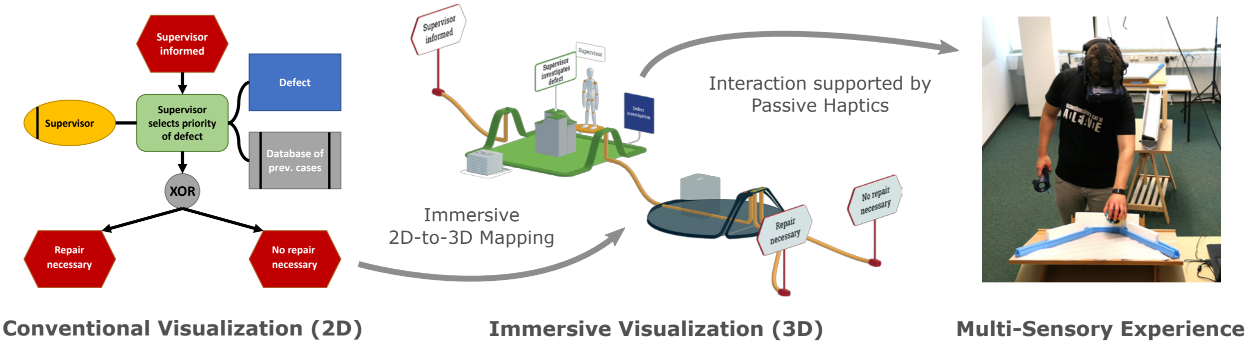

Fig. 1. We propose a system that turns the exploration of arbitrarily complex process models into an interactive multi-sensory virtual reality journey. Process models are traditionally communicated through 2D visualizations of their underlying graph structure (left image). The introduced system, in contrast, automatically generates an immersive virtual environment from any given process model (center image). The resulting 3D representation can be interactively explored by the user. Motivated through a basic gamification element and supported by auditory, vibrotactile and passive haptic feedback, our system turns learning a process into a multi-sensory virtual reality experience (right image).

Abstract— In many professional domains, relevant processes are documented as abstract process models, such as event-driven process chains (EPCs). EPCs are traditionally visualized as 2D graphs and their size varies with the complexity of the process. While process modeling experts are used to interpreting complex 2D EPCs, in certain scenarios such as, for example, professional training or education, also novice users inexperienced in interpreting 2D EPC data are facing the challenge of learning and understanding complex process models. To communicate process knowledge in an effective yet motivating and interesting way, we propose a novel virtual reality (VR) interface for non-expert users. Our proposed system turns the exploration of arbitrarily complex EPCs into an interactive and multi-sensory VR experience. It automatically generates a virtual 3D environment from a process model and lets users explore processes through a combination of natural walking and teleportation. Our immersive interface leverages basic gamification in the form of a logical walkthrough mode to motivate users to interact with the virtual process. The generated user experience is entirely novel in the field of immersive data exploration and supported by a combination of visual, auditory, vibrotactile and passive haptic feedback. In a user study with N = 27 novice users, we evaluate the effect of our proposed system on process model understandability and user experience, while comparing it to a traditional 2D interface on a tablet device. The results indicate a tradeoff between efficiency and user interest as assessed by the UEQ novelty subscale, while no significant decrease in model understanding performance was found using the proposed VR interface. Our investigation highlights the potential of multi-sensory VR for less time-critical professional application domains, such as employee training, communication, education, and related scenarios focusing on user interest.

Index Terms—Virtual reality, multi-sensory feedback, passive haptics, immersion, business process models, immersive data analysis

1 Introduction

With the rise and maturation of virtual reality (VR) technology, a novel human-computer interface emerged which lets users experience immersive virtual 3D environments (VEs). Multi-sensory systems that stimulate the visual, auditory and haptic senses allow visitors of VEs to feel a sense of presence [30] and interaction techniques with haptic feedback transform users into immersed actors in these virtual worlds. Such unique features distinguish VR from traditional 2D interfaces and open up novel design spaces. Besides entertainment, VR also comes with the potential to revolutionize the way we experience digital data in professional contexts or during our education. However, in many application areas, the potential of VR as an immersive interface for digital data exploration has not yet been studied sufficiently.

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This holds also for the professional domain of *process modeling*. Process models are abstract representations of arbitrary sequences of events and their dependencies. In many domains, they are the central representation format for professional documentation, communication, analysis, optimization, and simulation of business processes. Process models are stored in a suitable representation format, which is readable for both humans and machines. A widely-used representation format is the notation as an *event-driven process chain* (EPC) [14]. EPCs represent processes in a graph structure with nodes and edges and as such, they are traditionally visualized as 2D graphs on desktop monitors, mobile devices or paper. Process models are not only used by process modeling professionals, but also explored by novice users not experienced in interpreting the semantics of a 2D process graph. When new employees in a company, for example, are acquainted with important processes as part of their onboarding, such as the accounting of a business trip or the re-ordering of new goods, laypersons need to internalize process models. The same applies to educational scenarios where students learn about process modelling. With increasing complexity, however, understanding a process represented as a 2D EPC graph can become difficult and cause frustration. However, in situations such as employee training, customer presentations or education, it is important to ensure a motivating and interesting user experience.

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In this paper, we investigate how immersive VR can change the way users experience the exploration of process models – proposing an entirely novel, experience-focused exploration interface leveraging multi-sensory feedback. We target the user group of non-specialists as they can draw less on previous EPC experience and consequently might especially benefit from a less formal process model exploration. We introduce a system that given an EPC as input automatically generates a VE that represent the process in 3D. Leveraging a combination of different locomotion techniques and gamification, our system allows users to explore the process and interact with it. With the goal to turn the exploration of a process into a virtual journey that is suitable for novice users, more enjoyable, more interactive and more memorable than the experience gained from traditional 2D graph representations, we additionally include two types of haptic feedback in the experience. By integrating a range of existing techniques like real walking, active and passive haptics that are known to support presence, we maximize the immersion of the system. We compare our novel VR interface to a traditional interface that allows users to explore the 2D graph representation on a tablet device and investigate the potential of an experience-focused VR interface for abstract data exploration.

Our contribution is twofold. Firstly, we introduce the concept and implementation of a novel multi-sensory VR system with haptic feedback for immersive process model exploration. To realize our solution, we build upon a combination of existing concepts, such as passive haptics, visual spatialization, basic gamification and different locomotion and remapping techniques. Secondly, we present the results of a user study with $N = 27$ participants evaluating our proposed interface.

Our findings highlight the benefits and drawbacks of our immersive exploration system. Obtained results show a central tradeoff between exploration efficiency and user interest as assessed by the novelty subscale of the User Experience Questionnaire (UEQ) [20, 27] that can serve as a basis for decision makers. Our findings inform when to prefer an immersive interface over a traditional visualization. Moreover, our results do not indicate a significant decrease in model understandability performance when learning a novel process in VR compared to a traditional interface – highlighting the potential of immersive data exploration systems for less time-critical, professional application areas.

2 Related Work

In the following, we briefly introduce process models and related work on how to measure process understandability. We further discuss literature on immersive data analysis, haptics in VR and solutions to navigate large VEs if only a small physical tracking volume is available.

2.1 Process Models and Model Understandability

In the domain of information professionals and business process management, process models are used to formalize arbitrary real-world procedures in a concise, abstracted format [26]. As such, the formal model of a process holds information about involved operational steps, stakeholders, decisions and dependencies. In professional domains, a process model might, for example, be used to describe how ordered goods are inspected and delivered in a store, or how a customer complaint is handled in a company's support center.

Several representation formats for business processes exist. In the context of this work, we considered a widely used standard format which depicts processes as *event-driven process chains* (EPCs) [14]. EPCs are a graphical representation format (see Fig. 1), similar to alternative process notation formats such as, for example, *Business Process Model and Notation* (BPMN) [24]. As such, EPCs lay out the process flow, involved steps and stakeholders in a graph structure. Graph structures are human- and machine-readable, which makes them particularly suitable for a range of application areas. Consequently, EPCs are widely used for education, documentation, evaluation, simulation, optimization and worker guidance [15].

While 2D representation formats, such as EPCs, are well established, they only target the visual perceptual channel to communicate processes and layout models in a flat structure. To understand complex processes, users face the challenge to analyze large 2D graphs and need to be familiar with the concept of EPCs and their formal semantics. For this reason, several research projects have investigated *process model understandability* in the past [12, 26]. Recker et al. found that process model understandability is influenced by several factors including, for example, previous process modeling experience and the use of English as a second language [26]. In 2012, Houy et al. conducted a review of 42 experiments on the understandability of conceptual models and distilled the various concepts of model understandability found in the related research in a central *conceptual model understandability reference framework* [12]. To study how immersive data exploration affects the performance of users in understanding and learning new processes, we base our evaluation on this well established framework. Specifically, our study collects data on all 3 of its main understandability dimensions (objective effectiveness, objective efficiency, and subjective effectiveness [12]) to assess how well users understand a process model when explored with our proposed VR interface.

2.2 Immersive Data Analysis

As the importance of VR in professional contexts increases, corresponding research is steadily gaining importance, for example to explore the potential of immersive visualization in the context of data exploration and analysis. The modern VR hardware and software technology stack allows immersion of users in various VEs [30] – be they simulations of realistic environments or abstract data visualizations. Researchers have used large-scale projection systems (e.g. CAVES) [17, 18] and head-mounted displays (HMDs) [32, 46] in the past to investigate immersive data analysis. In previous work, for example, Zielasko et al. [46] explored hands-free navigation methods for large 3D graph data sets in the context of HMD-based immersive data exploration. In contrast to our interface, however, their work only focused on scenarios with users being seated and did not investigate the domain of EPCs [45]. Similar to navigation in realistic VEs, navigation through immersive data sets also yields the risk of cybersickness. In this context, adaptive field-of-view reductions have been proposed to mitigate cybersickness during immersive data analysis [47]. Moreover, previous work has highlighted the importance of immersion in the context of VR data investigation [17, 18]. For this reason, we designed our EPC exploration interface so that ideal conditions for the user to feel present are provided – leveraging multi-sensory feedback. Sousa et al. explored the use of VR for the immersive display of tomographic data for radiodiagnostics [32]. Their prototype integrated haptic feedback during data exploration as users touched a physical desk to perform gestural input. Similarly, Zielasko et al. [45] also proposed to represent physical objects, like desks, in the VE during data exploration to provide tangibility. In previous conceptual work, Zenner et al. [40] proposed a basic concept for how process model data can be communicated leveraging immersive VR and haptic interactions. Their proposed concept, however, was only partly implemented and not evaluated. Building on this previous conceptual work, we present the concept and implementation of a fully functional system for immersive EPC exploration. To validate our system and to study its effect on process model understandability, we further conducted a user evaluation.

2.3 Haptic Feedback for Virtual Reality

To maximize the user's sense of presence [30], our system provides the user with an additional feedback dimension beyond visuals and sound. Research on haptic feedback in VR has shown that haptics can increase immersion substantially [13], and approaches are broad and varied. Solutions are typically categorized along a continuum spanning from active to passive haptic feedback [42].

Active haptics leverages computer-controlled actuation to render a range of haptic sensations to the user [33]. Actuation through grounded [37] or body-worn devices [21], for example, can be used to push or pull the user's skin or body parts to convey tactile (e.g. using active vibration [6]) or kinesthetic sensations (e.g. by pushing against the user [37] or using electrical muscle stimulation [21]). While vibrotactile feedback is often easy to integrate and comes at a low cost, generating kinesthetic perceptions often requires complex, large, expensive and potentially dangerous hardware such as robotic arms.

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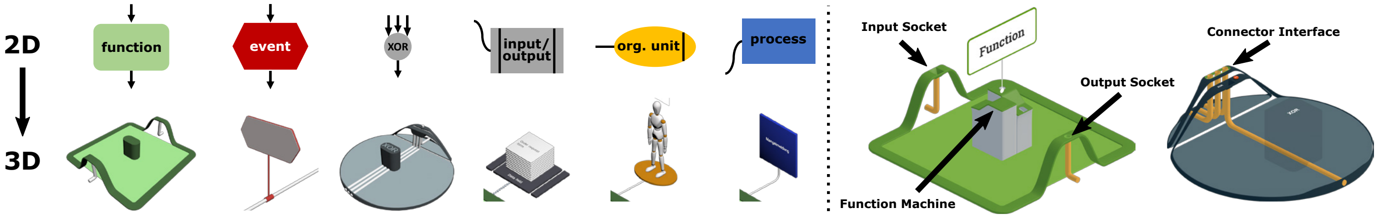

Fig. 2. Left: Traditional 2D EPC elements and corresponding 3D representations. Right: Interactive elements on function and connector platforms.

Moreover, complex simulations of the underlying physics are required to precisely control the involved actuators [33].

Passive haptics contrasts with active haptics in that it does not involve any actuation. Instead, users perceive the VE by touching and interacting with physical proxy objects that represent virtual objects in the scene. The approach was first proposed by Hinckley et al. [9] in 1994 and further research [10, 13] showed that passive haptic feedback can increase the immersion of VR systems. Crucial for passive haptic experiences is the spatial registration of a real proxy and its virtual counterpart [41]. Also, previous research has investigated the impact of real-virtual mismatches [28]. In this context, Simeone et al. [28] introduced the concept of *substitutional reality*. The authors propose VEs that automatically adapt to the physical environment of the user, substituting the real objects in the room with suitable virtual objects that match the setting of the VR experience. Interaction with props allows for very realistic tactile and kinesthetic perceptions when used in VR. At the same time, the approach is computationally lightweight, only requiring precise tracking of the proxies. Moreover, research has found the dominant influence of vision on perception to allow for certain real-virtual discrepancies to go unnoticed by users [7, 44]. The drawback of conventional passive haptics is the number of props required to represent large VEs and its inflexibility as a result of utilizing fixed and static real-world objects.

To overcome these issues, a range of mixed haptic feedback approaches exists. In encountered-type haptics [22, 35], robotic actuation by robotic arms [2], roving robots [29] or aerial drones [1, 11, 39] is leveraged to dynamically present proxy objects to the user during interaction in VR. To reduce the number of different proxies required when simulating a variety of objects, the concept of dynamic passive haptic feedback (DPHF) was introduced in 2017 [42, 43], promoting the use of self-transforming proxies. Cheng et al. [5] investigated how motor-driven actuation of proxies can be substituted by human actuation. With *TurkDeck*, they present a system in which non-VR bystanders relocate physical proxies to create a passive haptic environment on the fly as the immersed user explores a virtual scene. Later, their system *iTurk* was used to study how VR users themselves can relocate and reconfigure passive props during a VR experience [4].

In our project, we include haptic feedback to enhance the immersion of the system. At the same time, we opt for an affordable solution that still provides a compelling experience. To cover the two extremes of the active-passive haptics continuum [42] , we decided to integrate passive haptic feedback and active vibrotactile haptics in our data exploration application. Similar to the *iTurk* system by Cheng et al. [4], our system lets users continuously reuse physical props to scale our solution to arbitrarily large process models.

2.4 Navigating Virtual Environments

Virtual environments can exceed the size of the available tracking volume tremendously. This is also the case in our process exploration system. Several techniques exist that compress the VE into the physical space available to the user. *Redirected walking* [19, 25] techniques manipulate the path the user walks in the real environment, for example by manipulating the user's visual perspective. Researchers have previously shown how to combine redirected walking techniques with passive haptics [16, 34]. Alternatively, *relocation techniques* have been studied that transport the user to different virtual locations [23] which can then be explored by *real walking* [36]. Locomotion techniques are further classified as subtle, i.e. going unnoticed by the user, or overt, i.e. being detectable [23]. When walking in the physical space, be it unmodified real walking or redirected walking, *resetting controllers* (e.g. *Freeze-Backup*, *Freeze-Turn*, or *2:1 Turn* [38]) aim to prevent users from leaving the physical walking areas by guiding them back towards the center of the real room [23].

Based on previous results that found natural walking to be superior in terms of presence compared to more stationary techniques [36], we decided to let users explore the process visualizations in our application on foot. To allow for natural locomotion, we decided to implement an established overt relocation method for long-distance travel in the VE (i.e. *teleportation*). This enables users to explore important parts of the process by means of natural walking and allows for a seamless interaction with passive haptic props. To reuse physical props throughout the virtual process, we combine a symmetrical physical setup with a *180° resetting controller* introduced in Sect. 4.3.2.

3 Event-Driven Process Chains (EPCs)

While a variety of notation formats for process models exist [14, 24], we focus our system on the immersive representation of *event-driven process chains* (EPCs) [14]. EPCs are a widely used standard representation format. They are very well suited for our investigation since they are concise, have different node types with different meanings, shapes and colors, use logical operators, and come with an appropriate number of nodes for VR visualization. Moreover, since graphs are common data representation formats in many domains, the exploration of graph-based EPCs might support a generalization of some of our findings to other domains with graph-based data visualizations.

Being a structured representation of a process, an EPC formally consists of *function*, *event*, and *logical connector* (*and, or, xor*) nodes. EPC nodes are connected by arrows that indicate the process flow. Further process details are added utilizing special node types like *organization unit*, *input*, *output*, or references to other process models. Fig. 1 (left) shows a traditional 2D visualization of a basic example. Different node types represent different process elements. *Events* have no duration associated with them and represent process states which can trigger functions. *Functions*, in contrast, can take time as they are active elements representing process activities. Each type of node is traditionally visualized with a different 2D shape and color. Complete process models consist of an alternating sequence of *events* and *functions*. Through *logical connectors*, the process flow might be split into multiple branches, or branches can be merged. Additional information is attached to functions in the form of connected information nodes (e.g. *organizational unit nodes*, *input nodes*, or *output nodes*).

4 Multi-Sensory Process Model Exploration

To turn the exploration of EPCs into an immersive, interactive and memorable VR experience, we introduce a novel multi-sensory VR system. Our exploration tool is designed to be used in the context of education (e.g. for students learning about the concept of process models), internal company training (e.g. to teach employees about new processes important for their work), or customer communication (e.g. to present process optimization results to clients, or to explain company-internal processes to a customer). Targeting primarily novice users with little or no experience in process model analysis, the system focuses on immersion and the user experience, enabling users to associate a personal experience with the explored process.

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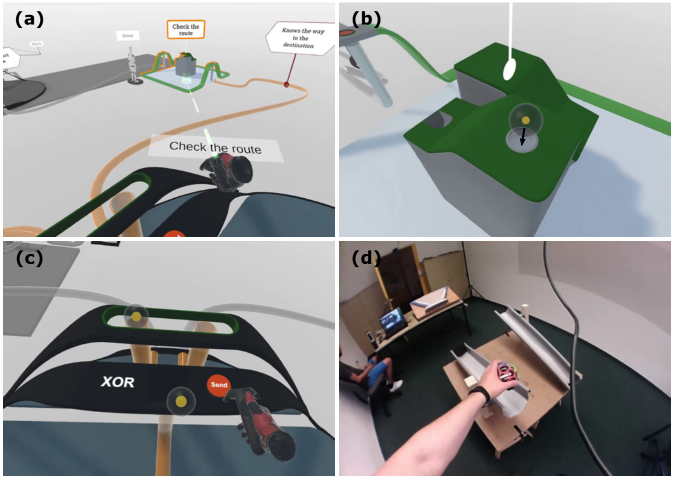

Fig. 3. View of the immersed user: (a) User teleports to the next node. (b) User puts the virtual information packet into a function machine. (c) User sends information packet only to the left child of the `xor` node. (d) Real-world perspective of the interaction in (b).

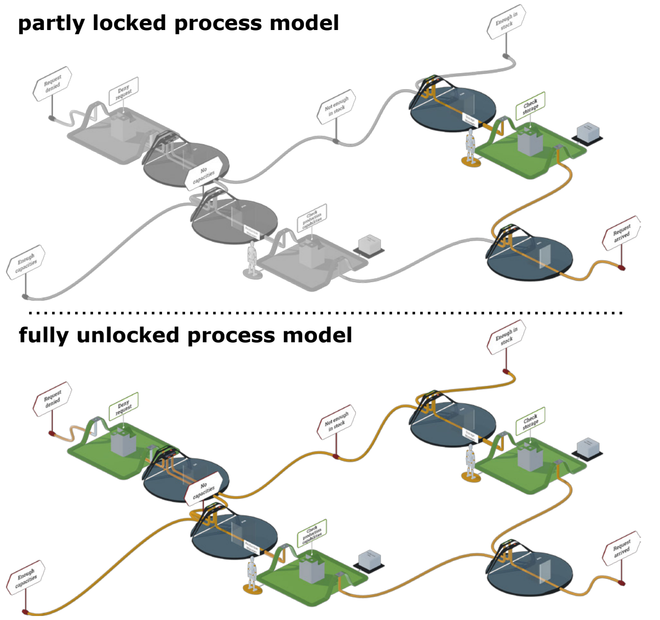

Fig. 4. *Logical Walkthrough* – Top: A partly locked process. Bottom: A fully unlocked process.

To this end, our interface lets users be an active part of the process. In our system, users transport abstracted information bits through the process following its operational flow and interactively experience the involved decisions. Based on the concept of *immersive process models* introduced in previous research [40], we propose a system which consists of 3 central components:

1. *2D to 3D Mapping* – A component responsible for an immersive visual 3D representation of the explored process in VR.
2. *Logical Walkthrough* – A component to motivate users to explore a process model with the primary objective to provide guidance while highlighting logical dependencies within the process flow.
3. *Haptic Interactions* – A component that supports immersion by transforming the experience into an interactive journey, allowing for haptic interaction with information bits and the process flow throughout the graph.

In the following, we describe these 3 main components and their implementation in more detail.

4.1 2D to 3D Mapping

The first component of our system is responsible for an immersive visualization of EPC models. To allow users to leverage their natural skills of spatial orientation while exploring process models, the first central component of our system spatializes the EPC to be explored. Given an EPC in a standard file format[1] as input, a parser loads the process model and a *2D to 3D Mapping* algorithm generates an immersive virtual 3D representation of the process as an output.

The mapping algorithm generates a virtual world in which the nodes of the EPC are represented by floating platforms. Functions and connectors are represented by room-sized, walkable platforms and events in the graph are displayed as virtual signs. Further node types like organization units, inputs or outputs are likewise represented by corresponding 3D objects. The visual design of the 3D elements is based on the original design of the 2D EPC elements to facilitate recognition and knowledge transfer. The individual elements of the 3D process model are connected by a virtual tube system – the 3D representation of the edges in the EPC graph. This tube system is used to transport information bits from the beginning of the process to the end of the process from element to element. Fig. 2 depicts how different 2D EPC structures are translated into corresponding 3D objects. Subsequent process elements are placed spatially below preceding elements to visualize the flow direction of the process through a descending platform layout. The center image in Fig. 1 depicts the descending 3D environment generated by our *2D to 3D Mapping* that corresponds to the 2D EPC shown on the left in Fig. 1.

4.2 Logical Walkthrough

The second central component of the introduced system handles the user's travel through the virtual process. For long-distance travel from one walkable platform to another walkable platform, our system implements the *teleportation*[2] metaphor. Fig. 3 (a) shows a screenshot. Being transported to the node of interest, users can freely and *naturally walk* within the boundaries of the corresponding virtual platform to benefit from the improved proprioception when physically walking in VEs. To avoid collisions with the physical surroundings, the size of the virtual platform corresponds to the physical tracking area.

While freely exploring nodes contained in a process model is one way to use our system, we additionally implemented a basic guidance system that enforces a logical exploration path through the graph called *Logical Walkthrough*. In the *Logical Walkthrough* mode, users need to carry information packages from the beginning of the process to the end, which are represented by a virtual sphere shown in Fig. 3 (b). Users start at the process root, the only *unlocked* node at the beginning, and can only visit already unlocked platforms in the process (see Fig. 4). Further process nodes can be unlocked node by node through correct interaction with function and connector platforms.

To unlock a node in the process, the information package must be transported to the respective node. Each 3D function platform contains an abstracted virtual machine that has to be operated interactively by the user, shown in Fig. 2 (right) and Fig. 3 (b). To proceed with an information package at a function platform, the user has to pick up the incoming information at the platform's input socket and drop it into the function machine on the platform (shown in Fig. 3 (b)). The machine processes the information and ejects a new information package. This processed information package is then to be picked up again by the user and sent through the virtual tube system to the next platform at the output socket to unlock the following node.

Similar to the interaction with functions, users also interact with the process on connector platforms. The system supports all logical operators: `or`, `xor` and `and`. In contrast to function platforms, con-

[1]EPCs represented in `.aml`, `.epml` or a specific `.xmi` data format are supported by our implementation.

[2]SteamVR implementation for the Unity engine: `https://valvesoftware.github.io/steamvr_unity_plugin/`

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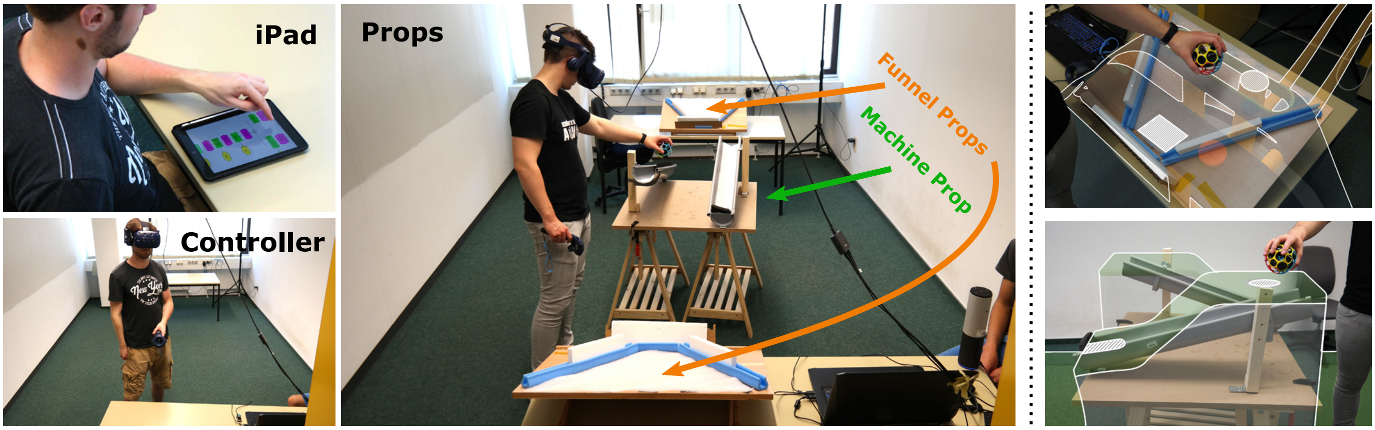

Fig. 5. Left: The 3 conditions tested in our user study. Top Right: Funnel prop overlayed with virtual operator interface. A user drops an information packet into an outgoing tube (hatched area on the right). When released, the ball will roll down the funnel prop where it can be picked up again later in the experience (hatched area at the bottom). Bottom Right: Machine prop overlayed with virtual function machine. A user drops an information packet into the function machine (hatched area on the right). The ball will roll down the prop as on a marble run and stop at the output of the function machine (hatched area on the left). At the output, the ball can be picked up again, now representing the ejected, processed information packet.

nectors can have several incoming or outgoing tubes. At connectors, the task of the user is to provide the necessary input for the connector according to its logical type. For an and connector with two incoming tubes, for example, the user has to send an information packet through each of the two incoming tubes, which leads the user to go through the corresponding previous process steps. When the input requirements of a connector are fulfilled, the user can decide how the information at the connector will flow further through the process. For this, users can interact with a connector interface on the platform. At an `xor` connector with multiple outgoing tubes (see Fig. 3 (c) or the image at right in Fig. 2), for example, the user can select to which of the following platforms an information package is moved. Fig. 2 (right) shows the involved elements of function and connector platforms.

While the difference between passive events (i.e. process states that take no time) and active functions (i.e. activities that take time to execute) is only weakly communicated with traditional 2D EPC representations, the interaction in our system facilitates the perception of functions as *active* components of the process to raise awareness for the relevant process steps. Furthermore, the interactions with connector platforms that control the process flow are designed to strengthen the understanding of logical decisions and dependencies occurring in the process. In sum, all these aspects of the *Logical Walkthrough* mode guide the user through the process in a logically meaningful order. The developed system transforms the exploration of a process from a passive observation of the 2D graph to an interactive experience in a 3D world. By this, our system aims to let users associate a personal and spatial experience with the explored process.

4.3 Haptic Interactions

The third component builds on the visualizations generated by the *2D to 3D Mapping* and the interactions with the platforms enforced by the *Logical Walkthrough*. Large-scale setups have been used in the past for immersive data analysis where space was required to immerse users with projection systems like CAVEs [17]. We propose to utilize the visual and auditory quality of modern HMDs and leverage the physical space for multi-sensory experiences by integrating haptic feedback.

While classical interfaces for process model exploration (e.g. 2D representations on paper or displays) only allow for visual inspection of the process model, our *Haptic Interactions* component additionally introduces the auditory and haptic dimensions. Specifically, users can perceive the interactions in the context of the *Logical Walkthrough* haptically, accompanied by sound effects. In our implementation, 2 levels of haptic feedback were implemented: active vibrotactile feedback and passive haptic feedback.

4.3.1 Active Vibrotactile Feedback

In a first mode, the developed system allows users to explore the 3D process model while holding an HTC Vive Pro Controller[3] in the hand (see *Controller* condition in Fig. 5). The controller triggers 2 different vibration patterns during interaction to signal either a positive or a negative outcome (successful interaction or unsuccessful interaction). For a successful interaction, a continuous vibration of $0.75s$ was triggered, while in the case of an unsuccessful interaction, 4 vibrations of $0.25s$ each were triggered with pauses of $0.25s$ in between. Similarly, basic sound effects were played back to support the positive or negative feedback. This feedback mode serves as a basic "notification" in response to virtual events and interactions.

4.3.2 Passive Haptic Feedback

In a second mode, the system leverages haptic props to increase the fidelity of the interactions with the virtual process, making them more physical and engaging. Here, the user explores the VE with an HTC Vive Pro controller in the non-dominant hand, leaving the dominant hand free to interact with physical props located within the physical tracking space. Conceptually, our approach is related to *iTurk* [4], as props are manipulated by the immersed user and reused throughout the experience. The image in the center of Fig. 5 (entitled *Props*) shows the symmetrical real environment in this haptic feedback mode. Following the classical approach of passive haptics [13], virtual objects in our application are not represented by 1-to-1 replications, but by 3 different types of low-fidelity props – i.e. physical proxies that allow for realistic interactions while being simplified and not representing the virtual counterparts in full detail:

1. **Mesh-Ball Prop:** The information packet is represented by a tracked physical mesh ball, shown on the right in Fig. 5. It is made out of a toy ball containing an HTC Vive Tracker[4] and allows for robust tracking even when carried with one hand.
2. **Funnel Prop (2x):** Haptic interactions at the input and output sockets of function nodes, and at the connector interface of connector platforms, take place at 2 funnel props placed at opposite ends of the tracking space. Each funnel prop has a tilted surface registered with the outgoing tubes in VR, and 2 funneling wooden slats. When dropping the information packet into any outgoing tube, the physical mesh-ball prop will drop onto the surface of the funnel prop at the location of the tube. Pulled down by gravity,

[3]HTC Vive Controller (2018):
`https://www.vive.com/us/accessory/controller2018/`
[4]HTC Vive Tracker (2018):
`https://www.vive.com/us/vive-tracker/`

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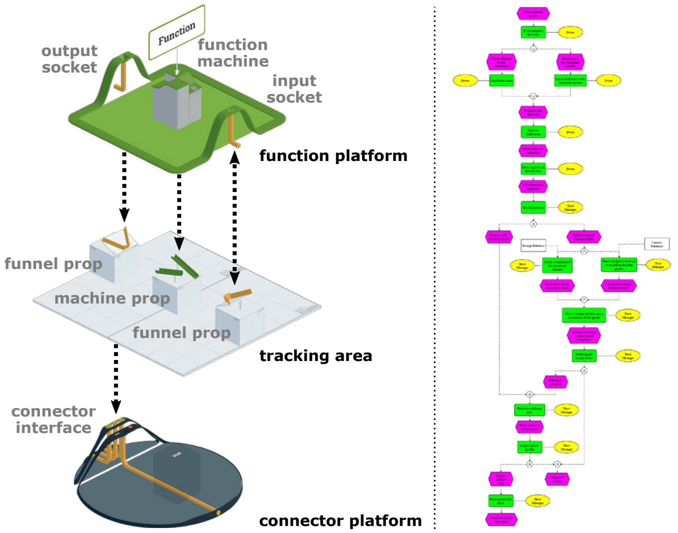

Fig. 6. Left: Spatial registration of the symmetrical physical setup with the walkable platform types. Right: 2D layout of the process used in our evaluation (generated using the *bflow* Toolbox* [3]). It describes the delivery of goods to a store (an extended and slightly modified version of the test process by Recker and Dreiling [26]).

the ball prop will roll down to the bottom of the funnel where it will be picked up again and reused later in the experience (e.g. at the input socket of the next platform).

3. **Machine Prop:** The machine in the center of function platforms is represented by the symmetrical prop shown in the bottom right image in Fig. 5, holding two tilted gutters. The upper ends of the gutters are registered with the input slots of the virtual function machine. When dropping the information packet in these slots, as shown in Fig. 3 (b), the physical mesh ball will roll down the gutter and end up at the lower end on the opposite side of the machine. The lower end is registered with the machine's output where the information prop can be picked up again later. This means that upon termination of the virtual machine's processing, it is the same mesh ball that physically represents the new information packet ejected by the machine.

Fig. 6 illustrates the real-virtual registration and the physical room setup. To enable exploration of arbitrarily large and complex EPCs with only a single mesh-ball prop, 2 funnel props and a single machine prop, a custom *resetting controller* was implemented. The resetting controller activates, for example, when the user stands in front of a platform's output socket and drops the mesh ball at an outgoing tube to send an information packet to the following platform. When teleporting to this platform, the resetting controller quickly fades the user's view to black, teleports the user's position to the target platform's input socket, rotates the view of the user by 180° and fades the view back in. As a result, the user can pick up the mesh ball just released at the previous platform's output from the new platform's input and continue the experience by turning around. These resets effectively mirror the real-virtual registration.

5 Evaluation

We conducted a user study to validate and evaluate the proposed system and to gain insights into the benefits and drawbacks of our novel EPC exploration interface. Within the scope of the study, the suitability of the VR system for mediating a process unknown to the user was tested. Our study scenario was motivated by the use case of familiarizing a new employee with a company process as part of the onboarding procedure – a scenario where content is to be communicated in a motivating and interesting way. To reflect this scenario, it was of particular interest to investigate how well users with little or no previous experience with EPCs and the domain of the test process can learn and understand a new process flow. Our goal was thus (1) to compare our novel 3D VR interface (*Controller* condition and *Props* condition) to a traditional 2D interface (*iPad* condition) and (2) to compare the 2 implemented modes of haptic feedback. We hypothesized that:

- **H1** Learning an EPC with our VR interface will require more time than with a traditional 2D interface due to the interactive experience involved.
- **H2** Learning an EPC with our VR interface yields better learning results than learning with a 2D interface, due to multiple senses being involved.
- **H3** EPC exploration with our VR interface offers an enhanced user experience compared to traditional 2D EPC interfaces, as it is designed to spark the interest of the user.
- **H4** Passive haptic feedback increases immersion when exploring EPCs in VR compared to vibrotactile controller feedback, as supported by prior research [13].

To investigate these hypotheses, our evaluation comprised 3 conditions in total. The *Controller* and *Props* conditions were both in VR and implemented as described before, providing vibrotactile feedback with the controllers and passive haptic feedback, respectively. In addition, a traditional *iPad* condition (shown in Fig. 5) served as a control condition in our experiment. For this, we displayed a 2D EPC visualization generated by the open-source EPC modeling application *bflow* Toolbox* [5] [3] on an Apple iPad. We chose a 2D representation on a mobile device since tablets represent a state-of-the-art exploration method which allows to inspect arbitrarily large EPCs with an interface fixed in size. In this *iPad* condition, users could freely explore the 2D graph using standard multitouch interactions such as scrolling and zooming, which additionally renders this kind of interface more flexible than paper while providing a more comfortable form factor and reading experience than desktop monitors.

The process used in the study is an extended and slightly modified version of a test process used in related research [26]. It depicts the process of delivering goods to a store, starting with the delivery driver and ending with the acceptance or rejection of the goods by the store manager. Fig. 6 (right) displays the 2D visualization of the full test EPC as it was shown in the *iPad* condition. The experiment was approved by the ethical review board of our faculty and took place in our lab.

5.1 Participants

A total of 29 volunteer participants recruited with flyers on the local campus took part in the study. We only included participants who had normal or corrected-to-normal vision, and who confirmed having neither a hearing impairment nor a haptic perception disorder that could affect their VR experience. Out of the 29 complete data sets, 27 of them (16 male, 11 female) were included in the final data analysis, while the data of 2 participants had to be excluded from analysis as the participants did not fulfill these aforementioned requirements for participation. The average age of the participants was 25 years (min. 22 years, max. 34 years); 2 participants were left handed, while 25 were right handed. Apart from 1 participant, all participants were inexperienced with EPCs and the domain of the test process. Moreover, 20 participants had very little or no experience with VR, while 7 were somewhat or very experienced in VR.

5.2 Apparatus

The experimental setup can be seen in Fig. 5. For the *iPad* condition, an Apple iPad was used, while for the *Props* and *Controller* conditions, an HTC Vive Pro[6] virtual reality system was set up. It consists of a Lighthouse Tracking System, an HTC Vive Pro VR HMD, 2 HTC Vive Pro Controllers and additional HTC Vive Trackers for tracking physical props. Our described VR application was developed using the Unity 3D engine. The passive haptic proxies used in the *Props* condition were assembled using readily available materials such as wood, styrofoam, plastic gutters and a toy ball, as can be seen from Fig. 5.

[5] *bflow* Toolbox:* https://github.com/bflowtoolbox/app/releases

[6] HTC Vive Pro System: https://www.vive.com/us/product/vive-pro/

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5.3 Procedure

Each participant was assigned to one of the 3 tested conditions (*iPad*, *Controller*, *Props*). For the *Props* condition, the experimenter calibrated the setup by spatially registering the physical props (2 funnel props, 1 machine prop) with the virtual objects in the scene (input and output sockets, connector interface and function machine) as shown on the left in Fig. 6. For the *Controller* condition, the experimenter cleared the tracking space of any physical objects and for the *iPad* condition, a table and a chair were prepared for the participant. After signing a consent form, a short introduction about the concept of EPCs was read by the participant, followed by a short tutorial on the respective method used to explore the process model.

When the introduction was completed, the task of the participants was to freely explore the test process with the assigned interface and to inform the experimenter as soon as they felt that they had understood the process. Participants were not required to visit every process platform in VR. The experimenter observed the exploration and recorded the time it took until the participant indicated having understood the process. Upon this indication, the participant stopped using the respective interface and answered a series of questionnaires on a laptop. The study took approx. 90 minutes per participant and each participant received a compensation of 10€ for their time.

5.4 Design

The study was designed as a one-factorial between-subjects experiment with the factor being the EPC exploration interface. The 3 conditions *iPad*, *Controller*, and *Props* were experienced by 9 participants each. Participants answered a set of questionnaires after exploring the EPC (in the order given below), to assess the dependent variables:

1. 3 central dimensions of the *conceptual model understandability reference framework* by Houy et al. [12]:
   (a) *Objective efficiency*, given by the time measured from the beginning of the process exploration until the participant indicated to have understood the process. (**H1**)
   (b) *Subjective effectiveness*, given by the response to a corresponding 7-point Likert scale question. (**H2**)
   (c) *Objective effectiveness*, given by the number of correct answers to 12 comprehension checkbox questions about the test process. Our questions were based on the questions used by Recker and Dreiling [26] in their previous work on process model understandability. (**H2**)
2. task load (measured by the NASA TLX [8] questionnaire) (**H3**)
3. immersion (measured by the SUS – Slater-Usoh-Steed Presence Questionnaire [31]) (**H4**)
4. user experience (measured by the UEQ – User Experience Questionnaire [20]) (**H3**)
5. qualitative responses from the participants, gathered through answers to experiment-specific questions and debriefing comments.

5.5 Results

We compared the 3 EPC exploration interfaces by conducting a series of statistical tests on the measurements of the dependent variables. Our significance level was set to $\alpha = .05$ and we conducted non-parametric Kruskal-Wallis tests with post-hoc Dunn-Bonferroni tests and Bonferroni-Holm correction (p') where applicable, to test for significant differences between conditions. In the following, we only describe the most relevant and significant results of our analysis.

The results for *objective efficiency*, i.e. the average time in minutes that participants took to understand the model, showed, that the exploration time of the 2D process graph with an *iPad* was significantly shorter than the exploration time in VR with *Controller* ($Z = 3.362, p' \leq .003, r = .79$) and *Props* ($Z = 3.868, p' \leq .003, r = .91$). However, our tests did not indicate any significant differences between the 3 interfaces concerning *subjective effectiveness* and *objective effectiveness*, i.e. the participants' performance in understanding the EPC and answering the understandability questions. Concerning *task load* (NASA-TLX) [8], again no significant differences were found. Fig. 7 shows the results for *objective efficiency* (on the far left) and *objective effectiveness* (second from left).

Table 1. Comparison of the *iPad*, *Controller*, and *Props* Conditions

Measure	Range		*iPad*	*Controller*	*Props*
Objective Efficiency	minutes	*M*	5.24	18.44	20.08
		SD	1.91	6.40	4.60
Objective Effectiveness	%	*M*	69.44	63.89	62.04
		SD	13.82	14.43	25.72
Subjective Effectiveness	1 to 7	*M*	6.56	6.22	5.44
		SD	.527	.667	1.333
NASA-TLX	0 to 100	*M*	43.62	38.14	48.44
		SD	12.84	14.97	18.71
UEQ Novelty (Interest)	-3 to 3	*M*	.17	.47	1.67
		SD	1.10	.99	1.19
UEQ Pragmatic Quality	-3 to 3	*M*	1.97	1.41	1.32
		SD	.58	.63	.95
UEQ Hedonic Quality	-3 to 3	*M*	.90	.75	1.72
		SD	.97	.68	1.12
SUS Mean	1 to 7	*M*	-	4.11	4.96
		SD	-	1.03	.85
SUS Count	0 to 6	*M*	-	1.33	2.89
		SD	-	1.80	1.69

A central aspect of our investigation was to evaluate the effects of our VR interface on the user experience, measured by the UEQ [20]. When analyzing the respective subscales we found the *UEQ novelty subscale* to be rated significantly higher for the *Props* condition than for the traditional 2D *iPad* condition ($Z = -2.560, p' \leq .03, r = .60$). Fig. 7 (second from right) visualizes the corresponding results on the respective scale from -3 to 3. This subscale encompasses 4 questionnaire items and measures a hedonic quality aspect of an interface. It is used to assess if a system is perceived as "*innovative and creative*" and whether it "*catch[es] the interest of users*" [27]. As such, it is a crucial measure for our experience-focused system. Other subscales of the UEQ did not yield statistically significant results. To better understand the qualities of the tested interfaces, we also analyzed the scores for *pragmatic quality* and *hedonic quality* provided by the UEQ (see left chart in Fig. 8). The *iPad* interface showed the highest ratings for pragmatic quality ($M = 1.97$, $SD = .58$), which supports the results for objective efficiency, but our tests did not show the pragmatic quality of the *Controller* ($M = 1.41$, $SD = .63$) and *Props* ($M = 1.32$, $SD = .95$) VR interfaces to be significantly different. Concerning hedonic quality, the VR *Props* condition scored highest ($M = 1.72$, $SD = 1.12$), supporting the UEQ novelty subscale results. As for pragmatic quality, however, corresponding tests did not show a statistically significant difference from the hedonic quality of the *Controller* condition ($M = .75$, $SD = .68$) or the *iPad* condition ($M = .90$, $SD = .97$).

Our evaluation of the system's immersion was based on the well-established SUS presence questionnaire [31]. To test if the type of haptic feedback affected immersion, we compared both the *SUS Count* and *SUS Mean* measures between the two VR conditions *Controller* and *Props* with non-parametric Mann-Whitney-U tests. SUS Mean ($M = 4.96$, $SD = .85$) and SUS Count ($M = 2.89$, $SD = 1.69$) immersion scores were higher for the passive haptic *Props* condition compared to the SUS Mean ($M = 4.11$, $SD = 1.03$) and SUS Count ($M = 1.33$, $SD = 1.80$) scores of the vibrotactile feedback *Controller*. However, differences were not statistically significant concerning both SUS Mean ($U = 59.5, p = .092$) and SUS Count ($U = 61, p = .063$). Table 1 summarizes the comparisons and Fig. 7 (on the far right) visualizes the SUS Count results.

In a concluding questionnaire and debriefing, we asked participants to reflect on the positive and negative aspects of the experienced interface and asked for any sickness symptoms experienced during the study. The very low overall sickness rating ($M = 1.41$, $SD = 0.93$) out of a 1-to-7 Likert scale self assessment confirmed the absence of cybersickness issues. The qualitative feedback of the participants is discussed in the following section.

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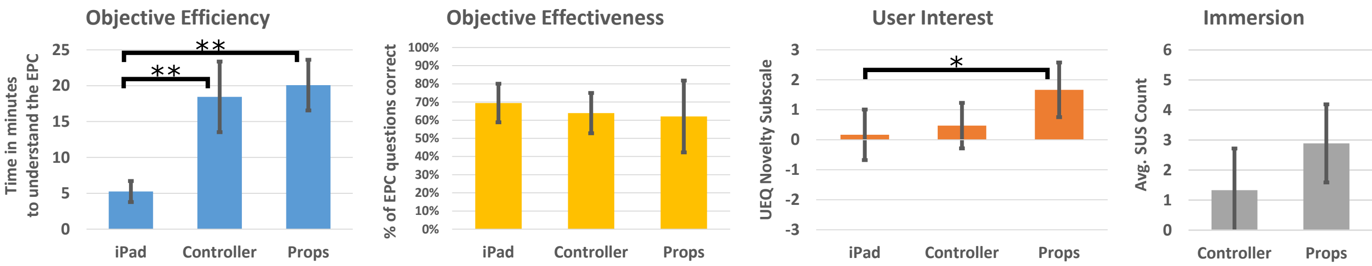

Fig. 7. From left to right: Between-condition comparison of the *objective efficiency* (i.e. time in minutes participants took to understand the process [12]), *objective effectiveness* (i.e. participant performance in answering process model understandability questions [26]), user interest (measured by the UEQ novelty subscale [20,27]) and immersion (given by the SUS Count [31]). Brackets indicate statistically significant differences ($p' < .05(*)$; $p' < .01(**)$). Error bars show 95% confidence intervals.

6 Discussion

Through our study we gained insights into the benefits and drawbacks of our proposed immersive VR EPC interface, and of the conventional 2D approach in comparison. Furthermore, we discovered a central tradeoff when these two approaches are considered against each other.

6.1 User Opinions: Benefits and Drawbacks of 2D and VR

From the observations in the context of our study, our results, and the qualitative feedback of our participants we could identify several important benefits and drawbacks of the tested approaches. We summarize them in the following, referring to comments from our participants.

The traditional 2D interface was appreciated by our participants for being *"easy to hold and carry around and [...] good for showing and interacting with other people to discuss the EPC"*. Moreover, a participant commented *"I do not have to learn some new interaction techniques as zooming etc works as expected"*. While the interface was described as *"easily understandable"*, others found that it *"gets confusing if the graph is very wide"* and *"if you look at multiple [...] even more complex EPCs you might start to get lost [...]"*. Finally, one participant wrote *"memorizing something works better for me if I actually interact a little bit with the things I have to memorize, instead of only reading"* – highlighting a need that our interactive VR interface aims to satisfy.

Participants described the immersive data visualization as *"clear"* and *"mak[ing] it easier to go through the steps afterwards again when needed"*. The *Controller* condition was perceived as *"a very useful tool"* for making new employees familiar with new processes in a company by one participant and was further characterized as *"new and different to other learning experiences"* and thus as being *"more attractive"*. Commenting on our gamification of the EPC exploration, one participant wrote that *"since you can't go further, when you ignore the operators, you quickly learn your mistake and can fix it – that makes it more memorable"*, which supports our experience design. Many participants also reported to connect a personal experience with the walkthrough – thinking of logical branching within the graph more as *"being in different places"* and *"making decisions that have different consequences"* (comments translated to English). This circumstance was summarized by one participant stating *"also it is more fun than staring at a piece of paper with the graphical representation as in the introduction"*. The possibility to interact with the process representation is one of the central differences of our VR system compared to 2D interfaces and was received well by most participants. In the *Props* condition, for example, one participant commented that it is *"easier to remember EPC because of physical interaction, more senses are involved in [the] experience [...]"*.

Concerning the limitations of the presented VR interface, drawbacks mentioned by our participants on the one hand encompassed general limitations of today's VR systems, such as uncomfortable HMDs (*"VR helmet is too heavy and it gets too hot inside"*). On the other hand, however, some participants also pointed out limitations specific to the implemented VR EPC interface. Supporting the results for *objective efficiency*, one participant noted that with a VR interface it *"takes time to have a look on all events [and] functions"*. Moreover, one participant criticized the recurring interactions implemented in our system, commenting that *"tasks are so standardised that you can get to the end of the process without thinking about the actual content"*. Another drawback that was mentioned is the limited mobility of our setup and the currently limited possibility for collaboration with others. Finally, one participant described the 180° remapping as *"confusing (but necessary)"*.

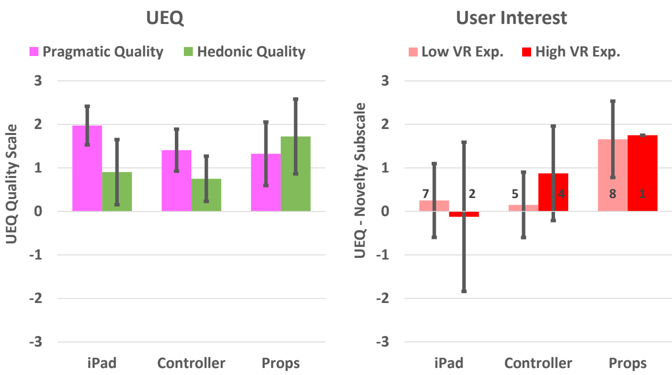

Fig. 8. Left: Comparison of the *pragmatic* and *hedonic quality* as assessed by the UEQ. Right: Comparison of the *user interest* as assessed by the UEQ novelty subscale between participants with low VR experience (self-assessments ≤ 3 on 1-to-7 Likert scale; $n = 20$) and participants with high VR experience (self-assessments > 3; $n = 7$). Labels show respective participant count; error bars show 95% confidence intervals (except rightmost bar).

6.2 When to Choose VR and When to Choose 2D?

The results of our user study make a very important and central tradeoff apparent, which is to be considered when deciding whether interactive VR should be used to learn an EPC, or whether sticking to a conventional 2D representation as a graph is more suitable. We could show that understanding an EPC of the size of our test process can be completed significantly faster with a traditional 2D interface than in VR (**H1**) (see Fig. 7, left). At the same time, however, the users' interest is significantly lower compared to using our proposed immersive interface with passive haptic feedback, as can be seen from the second chart from right in Fig. 7 (**H3**). Depending on the scenario, an interface that does not catch the interest of users might lead to them being demotivated and not paying attention to the communicated information. This would be detrimental and counterproductive, for example, in educational scenarios, when an employee is familiarized with changes in a company process relevant to his work, or when results of a process optimization are presented to customers. Visual analysis of the right chart in Fig. 8, further provides indication that the observed increase in user interest is not only a novelty effect of experiencing VR in general. While low participant counts disqualify a more detailed statistical analysis of the

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impact of VR experience on user interest, a trend of increased user interest in the *Props* condition is visible in Fig. 8, independent of the participants' VR experience. The plots for non-experienced and experienced VR users both closely resemble the general tendency observed in Fig. 7 (second from right). That said, we also like to stress that our question for previous VR experience did not explicitly probe the participants' prior experience with haptic proxy interaction, leaving the impact of a potential novelty effect related to the use of passive haptics unclear and to be explored in future work.

Concerning the EPC learning performance, our study results could not show **H2**. However, it is interesting to note that concerning the actual performance of the users in understanding the depicted process, we could not detect any significant differences with our study of $N = 27$ participants between 2D and VR, as apparent from Fig. 7 (second from left). Instead, we found very similar model understandability performances across conditions. While this does not prove the absence of performance differences and further investigation with higher participant counts is required in future work, the fact that differences did not become statistically striking with $N = 27$ provides initial support for the assumption that an immersive VR interface can be a suitable alternative to conventional 2D EPC interfaces in certain situations. It is this tradeoff between *efficiency* and *user interest* that represents the central finding of our evaluation.

While users could fall back to conventional 2D interfaces for time-critical EPC tasks, an immersive VR interface could be the first choice for less time-critical application scenarios such as presentations to customers, training and onboarding of employees, education, communication and related scenarios, to leverage the improved user experience. While not statistically significant, our results concerning pragmatic and hedonic quality as assessed by the UEQ and shown in Fig. 8 provide further support for this, as do the qualitative comments of our participants in debriefing after the study.

6.3 The Impact of Passive Haptic Proxies

Our analysis of immersion did not yield statistically significant results and consequently we could not show **H4**, but visual analysis of the corresponding plot on the far right in Fig. 7 indicates a tendency. The average SUS Count of participants in the *Props* condition was more than double the corresponding value in the *Controller* condition. Based on this result, we assume that passive haptic feedback can increase the user's sense of presence – an assumption also supported by the findings of previous research [10, 13]. Referring to the observed immersion ratings, we suggest to implement a passive haptic feedback environment when experience-focused VR is used as a data analysis tool, instead of a solution that is based solely on controllers, in order to attempt a maximization of immersion.

7 Conclusion & Future Work

The investigation of process models is an important aspect in many professional domains, and 2D graph-like representations are the currently established standard interface for their exploration. As a result, only the visual perceptual channel of the user is involved. In this work, we introduced the concept and implementation of a novel VR system for abstract data exploration, designed to provide an immersive, memorable, and interactive experience when exploring and learning process models. In contrast to traditional 2D visualizations of processes as graphs, our investigated system provides a multi-sensory interface that enables users to experience the graph representation of process models in a spatial virtual environment and allows them to interact with it. A *2D to 3D Mapping* component automatically generates immersive 3D visualizations from standard process model representation formats. It generates an environment of room-scale floating graph nodes which are connected by tubes to transport information packets through the virtual process model. Using gamification, teleportation and natural walking, the *Logical Walkthrough* component lets users explore process models in a logical, meaningful order and enforces the correct handling of logical decisions. Finally, we implemented two levels of *Haptic Interactions* to increase the sense of presence when interfacing with the process components. We explored vibrotactile feedback conveyed through standard VR controllers and a more sophisticated passive haptic feedback. Our interface leverages physical proxies for interaction with the virtual representation of information flowing through the process. In this context, the utilization of the marble run principle using symmetrical, uneven, funnel-shaped or gutter-shaped props in combination with a tracked spherical prop is, to the best of our knowledge, novel. Our implementation effectively compresses arbitrarily large process models into a limited physical space with passive haptic feedback. The proposed interaction concept further represents an evolution of classical approaches to passive haptics, addressing scalability and reusability issues. Our system implements a 180° resetting controller to enable the exploration of arbitrarily large processes in a limited physical space by continuously remapping the virtual scene to physical proxies.

In a user evaluation with $N = 27$ participants, we compared the effect of our VR interface on model understandability and user experience to a traditional 2D interface on a tablet device. Our results indicate a central tradeoff between *efficiency* and *user interest*, but did not indicate significant differences in model understandability performance across the tested conditions *iPad*, *Controller* and *Props*. Based on these results, we assume that multi-sensory and experience-focused data exploration interfaces in VR, such as the presented system, can be suitable alternatives to established 2D interfaces in certain situations. We imagine such interfaces to be of particular value for less time-critical applications such as customer presentations, training, communication, education, and related scenarios focusing on user interest.

Based on the promising results of our evaluation, we plan to continue our investigation of experience-focused data analysis that involves multi-sensory feedback. We will investigate how multiple users can participate in the experience, either by collaborating in VR or through collaboration of non-immersed and immersed users. Moreover, we plan to study and compare the short-term and long-term learning effects of efficiency-focused 2D and experience-focused VR exploration interfaces, as well as the scalability of the presented approaches. Future work might also investigate immersive process visualizations that are less generic but tailored to the actual process, potentially in combination with an EPC minimap to support orientation. Users could, for example, carry virtual versions of the documents or objects associated with the process through the VE, meeting virtual avatars of the actual persons involved in the real process. In addition, animations could simulate the duration of individual process steps to highlight time bottlenecks in the explored processes. By integrating features known from editor applications, the presented system could eventually evolve to a fully featured VR tool for immersive process modeling.

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References

[1] P. Abtahi, B. Landry, J. J. Yang, M. Pavone, S. Follmer, and J. A. Landay. Beyond the force: Using quadcopters to appropriate objects and the environment for haptics in virtual reality. In *Proc. CHI*, pp. 359:1–359:13. ACM, New York, NY, USA, 2019. doi: 10.1145/3290605.3300589

[2] B. Araujo, R. Jota, V. Perumal, J. X. Yao, K. Singh, and D. Wigdor. Snake Charmer: Physically enabling virtual objects. In *Proc. TEI*, pp. 218–226. ACM, New York, NY, USA, 2016. doi: 10.1145/2839462.2839484

[3] C. Böhme, J. Hartmann, H. Kern, S. Kühne, R. Laue, M. Nüttgens, F. J. Rump, and A. Storch. bflow* Toolbox - an open-source modeling tool. In *Proc. BPM Demonstration Track*, pp. 46–51, 2010.

[4] L.-P. Cheng, L. Chang, S. Marwecki, and P. Baudisch. iTurk: Turning passive haptics into active haptics by making users reconfigure props in virtual reality. In *Proc. CHI*, p. 89. ACM, 2018. doi: 10.1145/3173574.3173663

[5] L.-P. Cheng, T. Roumen, H. Rantzsch, S. Köhler, P. Schmidt, R. Kovacs, J. Jasper, J. Kemper, and P. Baudisch. TurkDeck: Physical virtual reality based on people. In *Proc. UIST*, pp. 417–426. ACM, 2015. doi: 10.1145/2807442.2807463

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[6] I. Choi, H. Culbertson, M. R. Miller, A. Olwal, and S. Follmer. Grabity: A wearable haptic interface for simulating weight and grasping in virtual reality. In *Proc. UIST*, UIST '17, pp. 119–130. ACM, New York, NY, USA, 2017. doi: 10.1145/3126594.3126599

[7] J. J. Gibson. Adaptation, after-effect and contrast in the perception of curved lines. *Journal of Experimental Psychology*, 16(1):1–31, 1933. doi: 10.1037/h0074626

[8] S. G. Hart and L. E. Staveland. Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In P. A. Hancock and N. Meshkati, eds., *Human Mental Workload*, vol. 52 of *Advances in Psychology*, pp. 139–183. North-Holland, 1988. doi: 10.1016/S0166-4115(08)62386-9

[9] K. Hinckley, R. Pausch, J. C. Goble, and N. F. Kassell. Passive real-world interface props for neurosurgical visualization. In *Proc. CHI*, pp. 452–458. ACM, New York, NY, USA, 1994. doi: 10.1145/191666.191821

[10] H. G. Hoffman. Physically touching virtual objects using tactile augmentation enhances the realism of virtual environments. In *Proc. VRAIS*, pp. 59–63. IEEE, 1998. doi: 10.1109/VRAIS.1998.658423

[11] M. Hoppe, P. Knierim, T. Kosch, M. Funk, L. Futami, S. Schneegass, N. Henze, A. Schmidt, and T. Machulla. VRHapticDrones: Providing haptics in virtual reality through quadcopters. In *Proc. MUM*, pp. 7–18. ACM, New York, NY, USA, 2018. doi: 10.1145/3282894.3282898

[12] C. Houy, P. Fettke, and P. Loos. Understanding understandability of conceptual models – what are we actually talking about? In P. Atzeni, D. Cheung, and S. Ram, eds., *Conceptual Modeling*, pp. 64–77. Springer Berlin Heidelberg, Berlin, Heidelberg, 2012. doi: 10.1007/978-3-642-34002-4_5

[13] B. E. Insko. *Passive Haptics Significantly Enhances Virtual Environments*. PhD thesis, University of North Carolina at Chapel Hill, USA, 2001.

[14] G. Keller, M. Nüttgens, and A.-W. Scheer. *Semantische Prozeßmodellierung auf der Grundlage "Ereignisgesteuerter Prozeßketten (EPK)"*. Veröffentlichungen des Instituts für Wirtschaftsinformatik, Universität des Saarlandes, Saarbrücken, Germany, Heft 89 (in German), 1992.

[15] S. Knoch, N. Herbig, S. Ponpathirkoottam, F. Kosmalla, P. Staudt, P. Fettke, and P. Loos. Enhancing process data in manual assembly workflows. In *Business Process Management Workshops. BPM 2018. International Workshop on Artificial Intelligence for Business Process Management (AI4BPM-2018), located at 16th International Conference on Business Process Management, September 9–14, Sydney, NSW, Australia*. Springer, Cham, 2018.

[16] L. Kohli, E. Burns, D. Miller, and H. Fuchs. Combining passive haptics with redirected walking. In *Proc. ICAT*, pp. 253–254. ACM, New York, NY, USA, 2005. doi: 10.1145/1152399.1152451

[17] T. W. Kuhlen and B. Hentschel. Quo vadis CAVE: Does immersive visualization still matter? *IEEE Computer Graphics and Applications*, 34(5):14–21, Sep. 2014. doi: 10.1109/MCG.2014.97

[18] B. Laha, K. Sensharma, J. D. Schiffbauer, and D. A. Bowman. Effects of immersion on visual analysis of volume data. *IEEE Transactions on Visualization and Computer Graphics*, 18(4):597–606, April 2012. doi: 10.1109/TVCG.2012.42

[19] E. Langbehn and F. Steinicke. Redirected Walking in Virtual Reality. In N. Lee, ed., *Encyclopedia of Computer Graphics and Games*, pp. 1–11. Springer International Publishing, Cham, 2018. doi: 10.1007/978-3-319-08234-9_253-1

[20] B. Laugwitz, T. Held, and M. Schrepp. Construction and evaluation of a user experience questionnaire. In A. Holzinger, ed., *HCI and Usability for Education and Work*, pp. 63–76. Springer Berlin Heidelberg, Berlin, Heidelberg, 2008. doi: 10.1007/978-3-540-89350-9_6

[21] P. Lopes, S. You, L.-P. Cheng, S. Marwecki, and P. Baudisch. Providing haptics to walls & heavy objects in virtual reality by means of electrical muscle stimulation. In *Proc. CHI*, CHI '17, pp. 1471–1482. ACM, New York, NY, USA, 2017. doi: 10.1145/3025453.3025600

[22] W. A. McNeely. Robotic Graphics: A new approach to force feedback for virtual reality. In *Proc. VRAIS*, pp. 336–341. IEEE Computer Society, Sep 1993. doi: 10.1109/VRAIS.1993.380761

[23] N. C. Nilsson, T. Peck, G. Bruder, E. Hodgson, S. Serafin, M. Whitton, F. Steinicke, and E. S. Rosenberg. 15 years of research on redirected walking in immersive virtual environments. *IEEE Computer Graphics and Applications*, 38(2):44–56, Mar 2018. doi: 10.1109/MCG.2018.111125628

[24] Object Management Group (OMG). Business Process Model and Notation (BPMN) – Specification Version 2.0.2. *Technical Report*, December 2013.

[25] S. Razzaque. *Redirected Walking*. PhD thesis, University of North Carolina at Chapel Hill, USA, 2005.

[26] J. C. Recker and A. Dreiling. The effects of content presentation format and user characteristics on novice developers' understanding of process models. *Communications of the Association for Information Systems*, 28(6):65–84, 2011. doi: 10.17705/1CAIS.02806

[27] M. Schrepp. User Experience Questionnaire Handbook – Version 7. Technical report, UEQ Document, 2019.

[28] A. L. Simeone, E. Velloso, and H. Gellersen. Substitutional Reality: Using the physical environment to design virtual reality experiences. In *Proc. CHI*, pp. 3307–3316. ACM, New York, NY, USA, 2015. doi: 10.1145/2702123.2702389

[29] A. F. Siu, E. J. Gonzalez, S. Yuan, J. B. Ginsberg, and S. Follmer. shapeShift: 2D spatial manipulation and self-actuation of tabletop shape displays for tangible and haptic interaction. In *Proc. CHI*, pp. 291:1–291:13. ACM, New York, NY, USA, 2018. doi: 10.1145/3173574.3173865

[30] M. Slater. Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, 364(1535):3549–3557, 2009. doi: 10.1098/rstb.2009.0138

[31] M. Slater, M. Usoh, and A. Steed. Depth of presence in virtual environments. *Presence: Teleoperators and Virtual Environments*, 3(2):130–144, 1994. doi: 10.1162/pres.1994.3.2.130

[32] M. Sousa, D. Mendes, S. Paulo, N. Matela, J. Jorge, and D. S. Lopes. VRRRRoom: Virtual reality for radiologists in the reading room. In *Proc. CHI*, pp. 4057–4062. ACM, New York, NY, USA, 2017. doi: 10.1145/3025453.3025566

[33] M. A. Srinivasan and C. Basdogan. Haptics in virtual environments: Taxonomy, research status, and challenges. *Computers & Graphics*, 21(4):393–404, 1997. doi: 10.1016/S0097-8493(97)00030-7

[34] F. Steinicke, G. Bruder, L. Kohli, J. Jerald, and K. Hinrichs. Taxonomy and implementation of redirection techniques for ubiquitous passive haptic feedback. In *Proc. CW*, pp. 217–223. IEEE Computer Society, Washington, DC, USA, 2008. doi: 10.1109/CW.2008.53

[35] S. Tachi, T. Maeda, R. Hirata, and H. Hoshino. A construction method of virtual haptic space. In *Proc. ICAT*, pp. 131–138, Jul 1994.

[36] M. Usoh, K. Arthur, M. C. Whitton, R. Bastos, A. Steed, M. Slater, and F. P. Brooks, Jr. Walking $>$ walking-in-place $>$ flying, in virtual environments. In *Proc. SIGGRAPH*, pp. 359–364. ACM Press/Addison-Wesley Publishing Co., New York, NY, USA, 1999. doi: 10.1145/311535.311589

[37] R. Q. Van der Linde, P. Lammertse, E. Frederiksen, and B. Ruiter. The HapticMaster, a new high-performance haptic interface. In *Proc. Eurohaptics*, pp. 1–5, Jul 2002.

[38] B. Williams, G. Narasimham, B. Rump, T. P. McNamara, T. H. Carr, J. Rieser, and B. Bodenheimer. Exploring large virtual environments with an HMD when physical space is limited. In *Proc. APGV*, p. 41. ACM Press, Tübingen, Germany, 2007. doi: 10.1145/1272582.1272590

[39] K. Yamaguchi, G. Kato, Y. Kuroda, K. Kiyokawa, and H. Takemura. A non-grounded and encountered-type haptic display using a drone. In *Proc. SUI*, pp. 43–46. ACM, New York, NY, USA, 2016. doi: 10.1145/2983310.2985746

[40] A. Zenner, S. Klingner, D. Liebemann, A. Makhsadov, and A. Krüger. Immersive process models. In *Extended Abstracts of CHI*, pp. LBW0128:1–LBW0128:6. ACM, New York, NY, USA, 2019. doi: 10.1145/3290607.3312866

[41] A. Zenner, F. Kosmalla, M. Speicher, F. Daiber, and A. Krüger. A projection-based interface to involve semi-immersed users in substitutional realities. In *2018 IEEE 4th Workshop on Everyday Virtual Reality (WEVR)*, March 2018.

[42] A. Zenner and A. Krüger. Shifty: A weight-shifting dynamic passive haptic proxy to enhance object perception in virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, 23(4):1285–1294, 2017. doi: 10.1109/TVCG.2017.2656978

[43] A. Zenner and A. Krüger. Drag:on: A virtual reality controller providing haptic feedback based on drag and weight shift. In *Proc. CHI*, pp. 211:1–211:12. ACM, New York, NY, USA, 2019. doi: 10.1145/3290605.3300441

[44] A. Zenner and A. Krüger. Estimating detection thresholds for desktop-scale hand redirection in virtual reality. In *Proc. VR*, pp. 47–55. IEEE, March 2019. doi: 10.1109/VR.2019.8798143

[45] D. Zielasko, M. Bellgardt, A. Meißner, M. Haghgoo, B. Hentschel, B. Weyers, and T. Kuhlen. buenoSDIAs: Supporting desktop immersive analytics while actively preventing cybersickness. In *Proc. IEEE VIS Workshop on Immersive Analytics*, 10 2017.

[46] D. Zielasko, S. Horn, S. Freitag, B. Weyers, and T. W. Kuhlen. Evalua-

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tion of hands-free HMD-based navigation techniques for immersive data analysis. In *2016 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 113–119, March 2016. doi: 10.1109/3DUI.2016.7460040

[47] D. Zielasko, A. Meißner, S. Freitag, B. Weyers, and T. W. Kuhlen. Dynamic field of view reduction related to subjective sickness measures in an HMD-based data analysis task. In *IEEE 4th Workshop on Everyday Virtual Reality (WEVR)*. IEEE, 2018.

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