Towards Collaborative and Dynamic Software Visualization in VR

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Abstract: To improve comprehension and maintenance of distributed software systems, some software visualization tools already bundle relevant information in a graphical way, but they either focus on the static structures and dependencies, or on tracing information. Our novel visual representation lifts the software city metaphor into VR and jointly addresses both static and dynamic behavioral aspects, such as call traces of microservice based systems. Users can navigate both the traces in the time domain and the static structure in the spatial domain. They can also collaborate with other developers. We argue that our 3D visualization provides the engineer with a better grasp on relevant information. With a controlled experiment we evaluated its user acceptance.

1 INTRODUCTION

Because of the longevity of complex software systems and a high fluctuation rate in teams, there is a need for an effective on-boarding of new developers so that they quickly and correctly understand the code and become productive. Industry often uses coaches to train newbies, either 1:1 or in groups. Coaches use tools like Jaeger (jaegertracing.io), Grafana Dashboards (grafana.com), etc. to illustrate structures, features, metrics, etc. of the system at hand.

Two threats limit the effectiveness of training-based approaches. (1) With many tools, each of which visualizing a certain aspect of the system, users easily get confused and often have to switch between tools. As this is error-prone and impacts productivity there is a need for tools that aggregate views. One of the challenges is to display all the dimensions of the information at once while keeping the result digestible. While 3D visualizations can exploit an extra axis, there are other issues such as occlusion of relevant background objects by less relevant foreground objects, etc.

We address (1) by exploiting recent advances in VR technology. We immerse the user into a virtual world whose artifacts represent characteristics of the software system. We tackle the resulting problems: (a) When—due to the headset—developers can no longer interact in the real world, there need to be means for collaboration in the virtual world (e.g., to share information and to explore the software together) and (b) users need to navigate in the virtual world. While the latter is well-understood in gaming scenarios, there is also the issue of time, which we discuss below.

Threat (2) is that current visualizations mainly focus on the static aspects of software. But microservice based architectures rely on interactions between program parts that are often set up dynamically and dispatched via frameworks like Spring (spring.io). These remain hidden in static visualizations.

We address (2) by visualizing traces, i.e., the dynamic behavior of requests through the distributed system. Users hence also need to navigate within the time domain.

2 RELATED WORK

First we summarize the state of the art in static 3D software visualization. We then briefly discuss work on the visualization of dynamic aspects.

To display abstract information such as software dependency graphs one needs a suitable visual representation, also called metaphor (Teyseyre and Campo, 2009). Examples are the *tree metaphor* (Reiss, 1995), the *nested box metaphor* (Rekimoto and Green, 1993), and the *city metaphor* that models classes as buildings in a virtual city and represents the package structure as districts of the city (Panas et al., 2003; Wettel and Lanza, 2007). This is best for our visualization as it offers both an intuitive and

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familiar environment and allows to display additional information such as call traces. The box metaphor is unsuitable due to its many visual occlusions. The tree metaphor causes too much visual noise as all the contains-relationships lead to too many branches.

With the city metaphor in a VR environment, there is also the need to navigate in the VR. To the best of our knowledge, there is no work yet that allows the user to walk around in a virtual software city. ExplorViz (Fittkau et al., 2013) uses hand gestures for moving the city while the user remains stationary (Fittkau et al., 2015). Instead, we focus on actual locomotion through the city.

Recent research covers locomotion in VR (Boletsis, 2017). “Flying”, i.e., moving the user’s position according to a joystick can cause nausea (Langbehn et al., 2018; LaViola, 2000) and has a lower user acceptance than teleportation. Here the user points at a target with the controller and presses a button to triggers the teleport action (Bozgeyikli et al., 2016; Langbehn et al., 2018). Natural walking is the best way to navigate in VR (Nabiyouni et al., 2015) although it is constrained by the available physical space. Redirected walking still requires more space than is available in most office environments (Langbehn et al., 2017). Natural walking requires modern room-scale-tracking headsets such as the Oculus Rift S or the HTC Vive family. We thus selected both the teleportation approach for long distance travel and natural walking for a more precise positioning when analyzing a small-scale structure.

In iViz (Donalek et al., 2014) a user can share a view on high-dimensional data with others. In SourceVis (Anslow et al., 2013) software engineers collaborate using large tablets. Users are in the same room and enrich their verbal communication with non-verbal cues, e.g., pointing gestures. Analogously, our VR must also provide visual communication cues. We use avatars to represent users’ positions and orientations (Jackson and Fagan, 2000; Carlsson and Hagsand, 1993). In the past the limited field of view of the HMDs has caused misunderstandings between collaborating users when they wrongly assume that their partners can see objects (Fraser et al., 2000). With the improvements of current VR headsets, displaying the avatar with its perceptible orientation should convey enough information. For efficient collaboration, however, more visual cues are needed (Cherubini et al., 2010; Clark, 2003), which fortunately can easily be mapped into our VR.

Current microservice architectures employ many services that are connected by networking frameworks. Processes cross service boundaries and their interaction is set up and dispatched dynamically. Tracing tools instrument the system so that all services report incoming calls on their interfaces/endpoints to a central collector. Responding to a request usually takes a sequence of calls to various endpoints, called a *trace*. It holds the dependencies between endpoints and the durations of individual endpoint calls, so-called *spans*.

Trace visualization is a rather new research area. ExplorViz (Fittkau et al., 2013) represents call relations between classes as streets. Users can play back traces by highlighting the respective streets. There is visual clutter because (a) streets overlap and (b) there is a visual entity for each software entity listed in a call trace, even for those missing in the static data (Fittkau et al., 2017). Traces thus include frameworks outside the scope of the visualized software system. Ciolkowski et al. (2017) address these shortcomings and use moving objects on the streets to indicate call directions. ThreadCity (Hahn et al., 2015) displays multiple threads of execution in 2D, with one lane per thread. Our trace visualization reduces visual clutter by only showing the relevant endpoints. We aggregate intermediate call targets that lie outside of the software system of interest (e.g., communication frameworks), see Sec. 5. Exploiting the third dimension, we display such calls as arcs above classes, making them easy to see and reducing occlusion problems.

In our trace visualization users can travel through the time frames of the traces. Since walking through a time portal (Herbst et al., 2008) is not well-suited for continuous time navigation, we use the controller’s circular scroll pad for time navigation.

3 SOFTWARE CITY IN VR

We use the Godot 3 game engine (godotengine.org) and Valve’s SteamVR (steamvr.com) to interface with VR headsets, e.g., the HTC Vive Pro, and to reveal the boundaries of the physical space to the user.

In our software city (Fig. 1) we map static structural elements such as packages or classes to districts or buildings. This preserves the hierarchical “contains”-relationship as districts can have subdistricts or buildings (cuboids). Buildings may have *courtyards* that contain smaller buildings to model inner classes. They have varying width, height, or color to map additional attributes of the underlying class. We use the width and height for depicting the number of methods of a class. The manually assigned color encodes the package to which a class belongs.

A static analysis gathers the calls between classes and uses them as the attraction force between buildings in a force-directed layout (Schreiber et al., 2019).

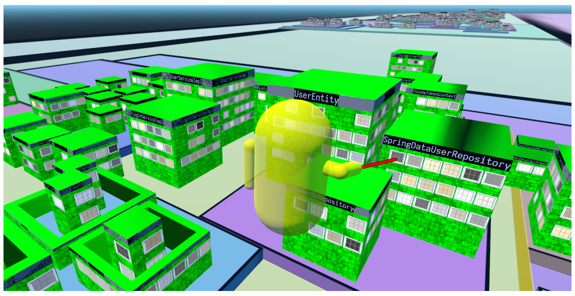


Figure 1: Software city with an avatar pointing at a building. Foreground: green buildings/classes of package `A`. Background: gray buildings/houses of package `B`. Lower left: class with an inner class in a courtyard.

4 COLLABORATION

While two users, e.g., a coach and a newbie, can view the same computer screen and discuss their findings directly, this is impossible in a VR environment that blocks all external visual influences. Hence, there must be a way to interact in the VR.

As users independently navigate in the software city and do not know what their collaborators can see, there may be misunderstandings when they discuss an artifact in the city, further aggravated by different zoom factors they can have on the city. To select between precise-and-slow movement and rapid movement through a model-landscape-sized software city, we offer a zoom feature that allows the user to “grow” or “shrink” at will. As this changes the view point of a user it must be conveyed to other participants.

To show a collaborator’s position, gaze direction, zoom factor, etc., we display an avatar in all other headsets (Fig. 1). This avatar also lets the users interact by pointing to entities in the software city with a virtual laser pointer triggered with a button on the VR controller. The avatar visibly points to the same entity in all other users’ views, regardless of their current zoom factors. Thus, it not only serves the purpose of pointing at entities, but also provides the user with familiar cues about their colleagues’ perspectives.

5 DYNAMIC TRACES

To visualize tracing information in 3D, results from the 2D approaches are only of limited use because both the static and the dynamic properties need to be represented in a combined view. Thus, a mapping scheme is needed that blends the tracing data with the static software structure. Two issues arise from that, namely (a) the occurrence of software entities in the traces that do not belong to the software system itself, but to libraries and frameworks used, and (b) a way must be found to display the time component of the traces. We present solutions to both issues below.

Trace Visualization by Means of Arcs. 2D trace visualizations like Zipkin (zipkin.io) or Jaeger use the *x*-axis for progress of time (Fig. 2(a)) and focus on revealing the hierarchical relationship of the spans. Calls between parts of the software look like calls to out-of-scope layers, e.g., communication frameworks. Instead, we assign spans to buildings: An arc from `A`’s building to `B`’s house indicates a call from `A::foo` to `B::bar`. Fig. 2(b) shows four simplified 3D snapshots taken at the same times T_i as the 2D view. While 2D visualizers leave it to the user to relate the traces to metrics in other tools (e.g., LoC), we jointly display the static structure and the traces, e.g., by mapping a LoC count to the height of a building.

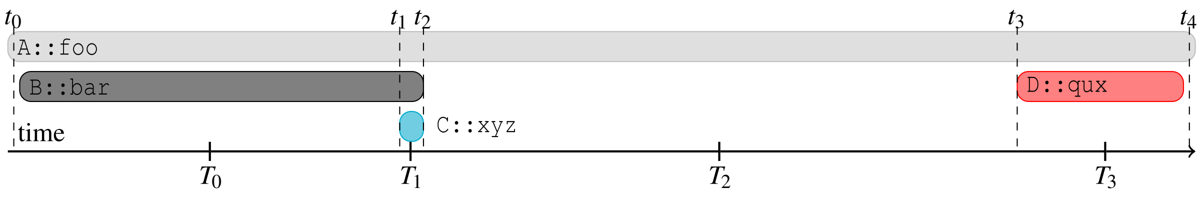
Time. Since representing the static software structure uses all three spatial axes, we use the time axis to represent time. As calls happen in the software, arcs appear and disappear while users are watching the dynamic behavior. The duration of the visibility of an arc corresponds to the duration of the respective call. As `C::xyz` in Fig. 2(a) is a rather short-running method starting at T_2, users see the corresponding bold arc in the snapshot at T_2 in Fig. 2(b) only for a short while before it disappears again. For a better overview, there are thin hints of arcs for future or past calls. At time T_2 both the arcs of `B::bar` and `C::xyz` are bold as the former calls the latter.

A user can also jump to arbitrary time points in the trace using the circular scroll pad on the controller. Time is shared and affects all users.

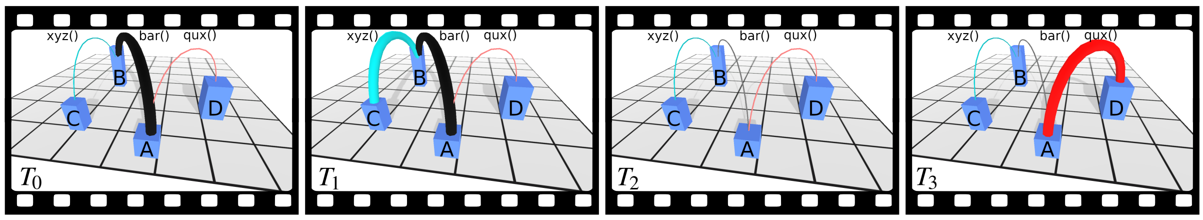
Time Modulation. If we used the real time to show spans with (dis)appearing arcs, short calls are easy to miss. This also holds for 2D, see `C::xyz` in Fig. 2(a). Conversely, `A::foo` is long and uneventful. We thus provide a seamless time modulation that scales from the real ratios (used in Fig. 2, $\alpha = 0$) to an artificial timing in which all events (dashed lines) are equally spaced. This emphasizes short spans and makes long spans less prominent (Fig. 3).

For $0 \leq \alpha \leq 1$ we modulate the span durations as follows: We sort all the starting and ending times of the spans such that $t_0 < t_1 < \ldots < t_n$ and derive the list of the durations $d_0 := t_1 - t_0, \ldots, d_{n-1} := t_n - t_{n-1}$. We then resize these durations according to α to become $\hat{d}_i := (1-\alpha)^{d_i}$. This yields the modulated span durations $\bar{d}_i := \hat{d}_i / \sum_{i=1}^{n-1} \hat{d}_i$ with their artificial time stamps $\bar{t}_i := \sum_{j=0}^{i} \bar{d}_j$.

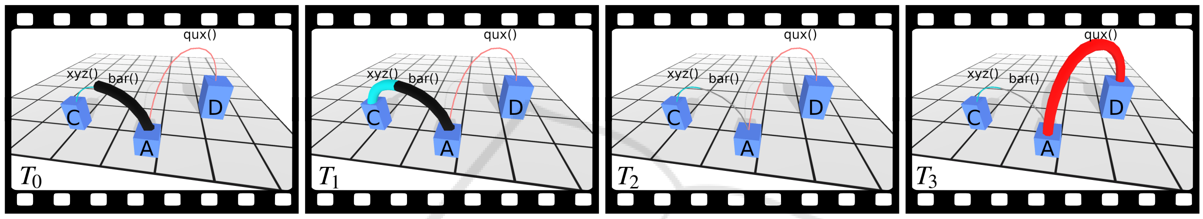
Reducing Clutter with Segmented Spans. Some spans use methods that belong to external frameworks and are thus less interesting, overwhelming the users



(a) Traditional 2D representation. The lengths of the spans correspond to the duration of calls ($\alpha = 0$).

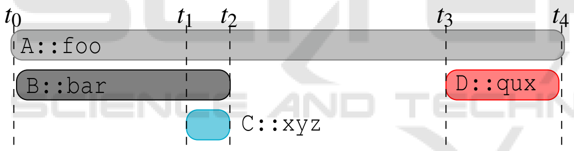


(b) Our 3D representation. 4 snapshots at times T_i. Simplified: no avatar, no method windows, no packages.

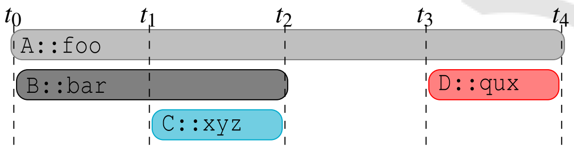


(c) Our 3D representation, if `B` is an intermediate framework.

Figure 2: Representations of a simple trace.



(a) Time modulation factor $\alpha = 0.5$.



(b) Time modulation factor $\alpha = 1$.

Figure 3: Time modulated 2D view of the trace in Fig. 2(a).

with too much detail in current 2D visualizations. For the example, if class `B` belongs to an external framework, it is hard to see in Fig. 2(a) that the framework `B` only routes the call between `A::foo` and `C::xyz`.

Fig. 2(c) shows how we use this idea to reduce the visual clutter: (a) We eliminate the building for `B`. The VR space is less populated and better to grasp. (b) A direct segmented arc from `A` to `C` at T_2 replaces the "detour" of the two arcs to `B` and back in Fig. 2(b, T_2) into irrelevant areas outside of the system under analysis. The direct arc reduces clutter. Its colored segments retain the information that a framework is involved. (c) We leave out calls that only go to the framework without going back to the system. There is no such call in the example.

To implement this reduction of visual clutter, we first flag all external framework nodes in the trace's call tree. As flagged nodes that are leaves of the call graph cannot be mapped to buildings (as external classes are not shown), we thus purge them (and their calls) from the trace. Second, we work on the remaining edges. An inner flagged node has n outgoing and one incoming calls. We remove it and replace each of the n pairs of in-/outgoing calls with a direct edge. The original calls (arc segments) as its attributes. We repeat this until no flagged node is left. Note that chains of flagged edges turn into direct edges with multiple segments, see Fig. 2(c, T_2).

In the example, the inner node `B::bar` is flagged because `B` belongs to the external framework. Hence its incoming call from `A` is fused with its outgoing call to the unflagged leaf `C::xyz`. Afterwards `B::bar` is purged from the trace, leaving a direct arc from `A::foo` to `C::xyz` with two segments.

6 EVALUATION

In order to answer the research question "How can VR provide an improvement in software visualization", we evaluated our approach in a controlled experiment. We chose a scenario, in which a coach explains the static architecture of a productive real-world software system *SmartPen* plus three exemplary call traces to a newbie in an 1:1 session.

SmartPen[1] is the backend of an app that recognizes a user's handwritten text, translates it into ASCII, identifies the intention of the text (e.g., creation of a to-do list), and sends it to an external app (e.g., a task app) that best matches the user's intention. Its static structure is composed of seven microservices (User Management, Device Gateway, Device Management, State Service, Push Notifications, Common Recognition Interface, and Writing History) whose details are irrelevant here. *SmartPen* uses *hystrix* as its load-balancer.

For the study we use dynamic trace data of the following three use cases: registering a new device, creating a new service token for a user, and processing of a complete user interaction, including saving it.

6.1 Participants

Before the experiment, all our 13 participants (11 ♂, 2 ♀, avg. age = 27.6, stdev. = 5.5; 5 PhD students, 6 master and 2 bachelor students, all in computer science with a background in software engineering) were asked to sign a form of consent (including a pre-experiment questionnaire) and were informed about anonymization and confidentiality. 7 participants had known issues with acrophobia (2), travel sickness (4), or dyschromatopsia (2); multiple answers. All participants had normal or corrected-to-normal (8) eye sight. Most had "some" VR experience (3 "none", 9 "some", 1 "lots"). While all had developed software as semester tasks or as their hobbies, they had less professional experience (2 "none", 7 "some", 4 "lots"). 10 felt focused while 3 felt less-than-average focused before we began the experiment.

All participants knew the setup and goals of the study. They knew that after the coaching session there would be questions about their comprehension of *SmartPen* and about our visualization's features.

6.2 Experiment

We randomly assigned each of the 13 participants to either the VR group (8) or the control group (5). Each participant was introduced to the experiment individually in a room with an obstacle-free VR area of about 2×2 m. All participants, regardless of their group, received a short introduction (recap on distributed architectures, call traces, and how they are visualized in traditional tools and in our tool). As all but one participants of the control group also wanted to use the VR system, we explained to all of them how to navigate in our VR. They had 5 minutes to get familiar with the VR controls for navigating and pointing.

Each of the VR-participants was then led into the lab (similar VR setup, but about 4×3.5 m). They were told to again set up the VR headset to their likings. For 15 minutes, the remote expert/coach then explained the architecture of the *SmartPen* software system and the traces. We used a telephone conferencing setup for the audio transmission and our tool's collaboration features for the visual channel.

Each of the control-participants was also led into the lab, but had to sit in front of a computer screen. The same remote expert then explained *SmartPen* in 15 minutes, this time using an audio/video conferencing tool, sharing with the participant a screen of Jaeger. Upon request by the participant, the coach adjusted the visible screen section accordingly.

With all the participants, the remote expert strictly followed a written script that dictated what to say. The scripts for both groups were identical, with minor variations in the wording (e.g., "trace span" vs. "arc" for the control/VR group). When asked something, the coach was only allowed to re-read parts of the script, but not to reformulate an explanation.

Right after the experiment, back in the real world or away from the computer screen, there were three post-experiment questionnaires. Comprehension questionnaire I (Fig. 4) checked whether the participant could reproduce the information received earlier. Acceptance questionnaire II (Fig. 5) asked for the participant's subjective assessment of whether they could follow the explanations, felt bored, etc. As all but one of the 5 participants of the control group later also tried out the VR variant, following the exact same procedure described above, a total of $8+4=12$ have answered the final feature questionnaire III (Fig. 6) regarding the usefulness of various features of the virtual and dynamic software city visualization.

There were no reports of any symptoms of nausea, VR sickness, etc. after the experiment.

6.3 Results and Discussion

Questionnaire I. Due to organizational issues we failed to present Q.I to the first 4 participants and thus have a reduced sample size of 5+4 for the VR+control group. Although this does not allow significant conclusions, we do not observe any indication that our

[1]The project, class and package names in *SmartPen* have been renamed (preserving semantics) in order to comply with non-disclosure agreements. Project size: ca. 100 software engineers, ca. 117k lines of code.

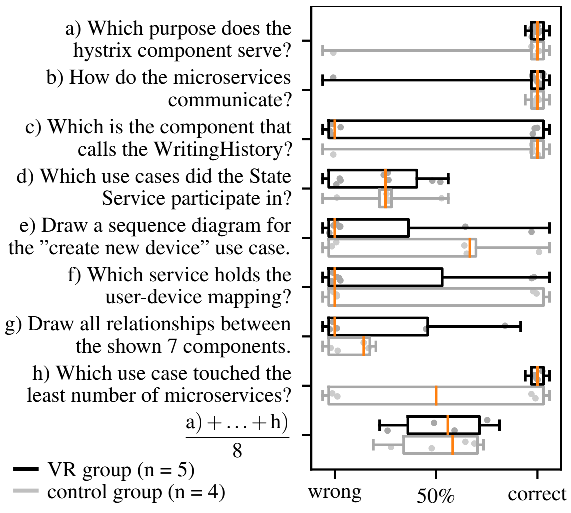


Figure 4: Questionnaire I (comprehension).

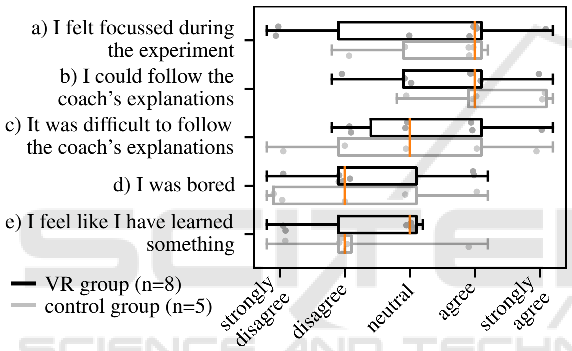


Figure 5: Questionnaire II (acceptance).

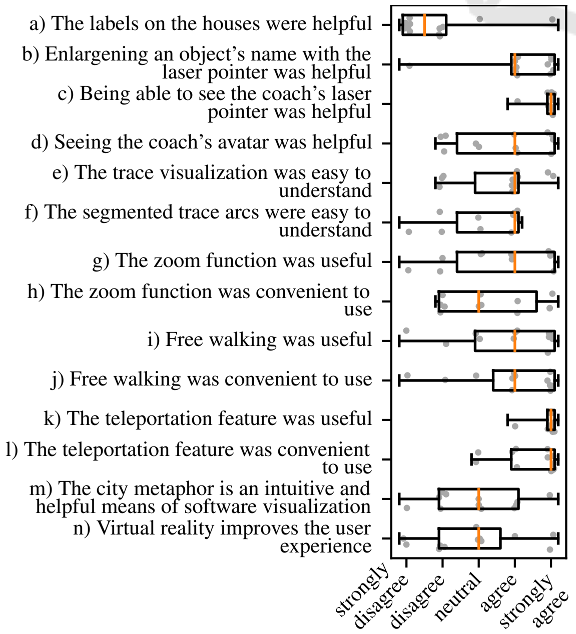


Figure 6: Questionnaire III (feature rating, $n = 12$).

visualization is any worse than traditional approaches in conveying information. We cannot explain why the VR group performed worse than the control group in question Q.I.e, whereas they did a lot better in Q.I.h. But on average (last pair of box plots), the participants were able to understand and memorize the system and its internal workings about equally well. The VR group achieved an overall correctness median of 58%; the control group reached 56%.

Questionnaire II. It seems like the ability to focus and to follow the remote expert's explanations was a bit better with the traditional screen-based visualization (Q.II.a-c). However, the VR participants at least "agree" that it was possible to follow the explanations. We explain the large spread in the answers from the VR group with the relative novelty of the VR medium as most of the participants had "little" or "no" pre-experience and probably were impressed by a room-scale VR setup. We suggest that some users were overwhelmed, wanting to explore the new technology without focusing on the explanations they were subjected to. This is in line with other studies, finding their users "curious" and "excited" (Merino et al., 2017). Future experiments should extend the period in which—after some training—the participants have unsupervised time to play.

While a majority of the control group "[strongly] disagrees" to have learned something (Q.II.e), our approach at least had a majority being "neutral" or "[strongly] agreeing". We argue that because of the visually more pleasing presentation, users felt that they could remember more of the information that was given to them. This is in line with research showing that supporting multimedial cues help people remember facts better (Mayer et al., 1996).

Overall the data suggests that our approach is able to present complex software relationships in a way that is well-accepted by the participants.

Questionnaire III. From the answers to Q.III we conclude that visualizing the coach with the avatar and its laser pointer are the key for collaborative software exploration in VR. Most of our users (Q.III.b-d) deemed this at least "helpful". This is not surprising since human collaboration relies a lot on visual cues (Clark and Brennan, 1991; Clark, 2003).

While the object names were an important hint to the user, having them attached to the tops of buildings was not helpful (Q.III.a). Most participants did not even notice their presence. Despite recent advances in VR headset resolution and quality, the text was still hard to read and thus useless. Our alternative was well-accepted (Q.III.b): When pointing with the laser pointer at an object, we show the name in a large overlay floating above the selected object.

All our navigation techniques (zoom, natural walking and teleportation) were "[strongly] agreed" to be helpful by a majority (Q.III.g-l). While we note a large spread in the answers with the other two techniques, teleportation was even "strongly agreed" to be useful by more than 75%. Probably many participants did not trust the boundaries shown by the VR system and were uncomfortable walking, fearing they would hit a wall. According to the recorded position logs many users picked at most two spots and teleported from there. Maybe an augmented or mixed reality solution that embeds the VR into a 3D model of the physical space can encourage users to better utilize the available space.

Most participants "[strongly] agree" that our visualization makes traces easy to understand (Q.III.e). The segmentation of the arcs to show external frameworks is a good way of representing such dynamic call relationships (Q.III.f).

In conclusion, most features implemented in our approach were well accepted by the participants.

Finally, although the majority of the participants was "neutral" about the usefulness of the city metaphor and the usage of VR to visualize software, this is still good news as our system is just a research prototype and can nevertheless already compete a with state-of-the-art 2D tool. Also, more participants from the VR group learned something new than in the control group (Q.II.e).

6.4 Threats to Validity

The selection of the participants might influence the result of the study. Some participants could be less competent than others. Random group assignment mitigated the issue. Participants in the VR group may have been more motivated as VR is often regarded as something new and exciting. We mitigated this by offering all participants to try the VR.

Another threat is that one of the authors was the coach, who may subconsciously have conveyed more information to the VR group. We eliminated this by restricting the coach to one written script so that all participants had exactly the same information.

The ability to focus on the explanations may have been impacted by disturbances such as people talking in the neighboring room. By randomly deciding whether the next participant will be from the VR or the control group and by coaching all participants in the same lab we minimized this influence.

Our results are neither skewed by a lack of motivation nor by fatigue: Half of the participants in both groups "[strongly] agree" to be feeling focused during the experiment; nobody was bored (Q.II.a,d).

Threats to the external validity are the selection of the participants by recruiting them on the university campus. This might result in an academic skew. Also, using just one software system *SmartPen* and three traces poses a threat. However, what strengthens the validity is that it is a real-world productive system and the traces illustrate non-toy use cases.

7 CONCLUSION

Understanding complex software systems requires expressive visualization techniques that combine both static information and dynamic tracing data. We described and evaluated a software visualization system in virtual reality that allows multi-user collaboration. We extended the well-researched software city metaphor to display tracing data, while reducing visual clutter by means of a pre-processing. Our system offers intuitive navigation through space using state-of-the-art techniques (natural walking and teleportation) and through time using a circular scroll pad.

We validated our system by means of a controlled experiment and drew conclusions from the user responses. We discussed which features were useful and how to improve others, and conclude that our proposed visualization technique is a step towards next-generation software visualization frameworks.

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