"Oh, that's where you are!" – Towards a Hybrid Asymmetric Collaborative Immersive Analytics System

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We present a hybrid Immersive Analytics system to support asymmetrical collaboration between a pair of users during synchronous data exploration. The system consists of an immersive Virtual Reality application, a non-immersive web application, and a real-time communication interface connecting both applications to provide features to facilitate the collaborators' mutual understanding and their ability to make (spatial) references. We conducted a real world case study with pairs of language students, encouraging them to use the developed system to investigate a large multivariate Twitter dataset from a sociolinguistic perspective within an explorative analysis scenario. Based on the results of usability scores, log file analyses, observations, and interviews, we were able to validate the approach in general, and gain insights into the users' collaboration with respect to awareness, deixis, and group dynamics.

CCS Concepts: • **Human-centered computing → Virtual reality**; **Collaborative interaction**; *Empirical studies in HCI*; *Collaborative and social computing*.

Additional Key Words and Phrases: asymmetrical collaboration, awareness, common ground, deixis, immersive analytics, spatial reference, virtual reality, 3D gestural input

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1 INTRODUCTION

Immersive Analytics (IA), an emerging field of research, has the potential to change drastically the way we explore, interact, interpret, and make meaning of data by utilizing immersive technologies, such as Virtual Reality (VR) [20]. Display and input devices that allow for immersive interaction, for instance head-mounted display (HMD) devices and tracking controllers, are now generally affordable and accessible—even on the ordinary consumer market. While gaming and entertainment are arguably a driving force behind the recent development of these technologies, there are also various non-entertainment related purposes, such as education [27], architecture [55], productivity [33], training [44], or data visualization [50], to name just a few. At a time when massive amounts of data within different scenarios and contexts are collected almost everywhere (often referred to as the *Big Data challenge* [7]), it is becoming increasingly important for researchers to have access to tools to visualize, understand, and make decisions from those data [13, 19, 39, 46]. Even though techniques such as machine learning and data mining are rapidly improving and can be used for assistance with pattern and point-of-interest (POI) discovery within big datasets, there is still a need for human interpretation, contextualization, and further meaning and decision making based on these discoveries and insights [25]. Consequently, both single tools and comprehensive workflows (consisting of multiple different tools) to support human users with the latter are desirable. Immersive visualization and interaction technologies hold potential to provide such tools in novel and engaging ways.

1.1 Research Challenges

Emerging 3D display and input technologies invite researchers to look into novel, intuitive, natural,[1] and engaging applications to analyze data [3, 18, 19, 46, 48]. Investigations are needed to explore methods to support three-dimensional (3D) data exploration within the context of IA, either adapted from existing ones, for instance the ones apparent in areas such as Information Visualization (InfoVis) or Visual Analytics (VA) [22], or built from the ground up. IA research is not intended to substitute or replace existing two-dimensional (2D) practices, but instead to add new 3D user interfaces (3D UIs) that *synergize and complement* the data exploration activity. Particularly within the scope of exploring big datasets, there is no single application or tool to satisfy all of a user's needs, but rather multiple ones are needed, each for their own purpose (using different views and interaction techniques) to support the user's problem-solving strategies, framing an overall greater analysis workflow [41]. There is huge potential for the interplay between new 3D UIs and established 2D practices, especially in regard to human-centered challenges, such as collaborative visualization and effective interaction [34]. Using HMD devices for data immersion in VR poses several design and interaction challenges for active collaboration between multiple users. Naturally, when wearing a HMD, the user is visually isolated from the real world surroundings and confronted with computer-generated content, by default creating a rather user-centered, single-user experience [18, 25]. Thus, many important collaborative information cues (facial expressions, body language, spatial references, and more) are no longer available. However, enabling multiple users to collaboratively explore and interpret data is often desired: (1) the analysis of large datasets requires a broad expertise, unfeasible to be covered by a single analyst [28, 56]; (2) collaboration is more effective than working alone [6], arguably because it is anchored within the human nature [42]; (3) besides perceptual and cognitive processes, visual analysis and decision making also involves social processes, such as analysts debating about the interpretation of data, providing individual and contextual knowledge [6, 26]. Consequently, more research is needed to address such multi-disciplinary challenges in the area of collaborative IA to bridge the gap between user-centered experiences and collaborative data analysis.

1.2 Research Focus

To address aspects of these research challenges, we investigate the application of VR, in particular using HMDs and 3D gestural input, in a scenario that supports the *explorative analysis* of data [1, Ch. 1] [53, Ch. 1]. Rather than having multiple users exploring data using the same VR interface, we envision a scenario where users collaborate in real-time (synchronous), each one using different tools and technologies (asymmetrical), in order to interact with the same data. For instance, while one user explores a dataset in 3D within VR (IA), a second user may explore the same data in a separate application in 2D (InfoVis, VA) at the same time. Both immersive and non-immersive applications have their own purposes and features, including unique advantages over the other.

[1]In our context, *natural* denotes no need for expertise in order to make use of a tool.

We implemented a system consisting of (1) an immersive VR application, (2) a non-immersive web application, and (3) a real-time communication interface connecting both applications to provide features to support the users' mutual understanding and their ability to make spatial references (according to the concepts of *Common Ground, Awareness, Reference, and Deixis* as described by Heer and Agrawala [26]). In order to validate our proposed idea and the developed system in a meaningful way that is relevant to the practical analysis of data in a real-world scenario, we conducted a user interaction study. The participants were first-year linguistics students working in pairs, encouraged to explore Twitter data with respect to language variability and the use of hashtags in tweets from a geospatial perspective within a sociolinguistic context. This enabled us to measure the usability [8] of the developed system, and to analyze aspects of their collaboration using observations, system log files, and semi-structured interviews.

2 RELATED WORK

2.1 IA and CSCW

IA is concerned with the exploration of new tools and techniques that promote analytical processes and reasoning with the aid of immersive technologies, uniting interdisciplinary research expertise from fields such as InfoVis, VA, Human-Computer Interaction (HCI), and VR [13, 20, 25]. Important physiological fundamentals about VR and the design of 3D UIs are described at length by LaValle [35] and LaViola, Jr. et al. [37]. Immersion has the potential to facilitate the exploration of data (e.g., depth cues as additional information dimension, presentation of data with spatial embedding, literally more space to arrange views, increased user engagement), prompting IA researchers to reconsider the value of 3D visualizations, since their application for data exploration is rather rare outside of Scientific Visualization (SciVis) [40]. Besides the actual visualization and interaction with data in the 3D space [11], another important aspect determining the success of IA is concerned with the collaborative capabilities of an IA system [6]. However, wearing a HMD to immersive oneself in the VR environment (visually) isolates its user from the physical surroundings. *Social VR* is concerned with investigating interaction mechanisms to overcome this drawback, but is still in its early stages [35, p.301]. Ens et al. [21] provide a comprehensive reflection on collaborative Mixed Reality (MR) in regard to CSCW. Within the scope of collaborative IA, insights from the area of CSCW can be informative, researching how computer systems can support collaborative activities conducted by more than one user. More specifically in this context, definitions for Collaborative Visualization [28], User-Centered Collaborative Visualization [12], and Collaborative IA [6] exist. Descriptive models and frameworks can assist with the measurement of collaboration, such as Johansen's [1988] time-space matrix, Gutwin and Greenberg's [2002] workspace awareness, Tang et al.'s [2006] and Isenberg et al.'s [2012] collaboration coupling styles, Neumayr et al.'s [2018] hybrid collaboration and coupling styles in partially distributed teams, or Lee and Paine's [2015] model of coordinated action. The importance of communication, coordination, and awareness within the collaborative sense-making activity are well highlighted [39]. Nevertheless, the human-centered evaluation of collaborative systems and its multi-disciplinary nature remains challenging [28, 34, 46].

2.2 Immersive Interaction and Collaboration

Churchill and Snowdon [14] discussed the nature of collaboration within virtual environments already in 1998, pointing towards the essential characteristics of collaborative work, emphasizing the need for appropriate information representation and communication tools to support collaborative work. Studies about asymmetrical interaction and collaboration using immersive technologies provide insights and design considerations in regard to aspects such as co-presence, awareness, leadership roles and task contribution, communication and collaboration, and co-manipulation of objects [15, 23, 45, 54]. Cordeil et al. [18] evaluated the collaborative aspects of two IA systems (CAVE and HMD) in terms of collaboration strategies, shared focus, completion time, self-perception of collaboration, proportion of oral communication, and balance of physical movements. Even though the users in the HMD scenario were not able to monitor each others facial expressions or body language, which are important during their communicative efforts to establish a *Common Ground* [26], no major issues regarding this limitation were detected within the scope of a low-level graph visualization task [18]. Immersive data exploration can facilitate the users' spatial understanding and retention of more structural information [5], and requires less effort and navigation to find information while also providing a larger subjective perception of accuracy and engagement [52]. Donalek et al. [19] explored the use of VR for data visualization with the aim to facilitate the user's visual discovery skills, also providing some preliminary insights towards collaborative aspects. Interactive techniques for data selection, navigation, filtering, or annotation, are fundamental for any IA system [11]. Streppel et al. [50] explored three concepts for immersive interaction (direct user interaction, physical controls, virtual controls) within the context of a software city application, finding no major preference of one concept over the other based on the subjective impressions of the study participants. Reski and Alissandrakis [47] investigated different input technologies (gamepad, 3D gestural input, room-scale VR) within the context of data exploration in VR, identifying a trend towards user preference for visual (virtual) representation of the input controls in VR, but no major preference in regards to the input control's physicality. Challenges and opportunities of immersive unit visualization are described by Ivanov et al. [30]. Cordeil et al. [16, 17] and Butcher et al. [10] recently presented tools to support visualization and fluid interaction with multivariate data in VR.

2.3 Prior Observations and Motivation

These recent advances in the research by the community (see Section 2.2) are exciting and encourage further investigations, particularly in regards to the initially stated advantages and challenges of enabling multiple users to explore data (see Section 1.1). Based on our prior experiences demonstrating VR applications, we made one particular reoccurring observation: A typical VR application allows a single user to immerse themselves in the virtual environment, often *mirroring* their view on a large display for bystanders to follow, but not providing them with any straight-forward means of engaging, communicating, and/or collaborating with the immersed user. To their own frustration, any such attempt turned out rather difficult to achieve, as the VR user was not able to successfully identify where the bystander's prompted POI was. There was either a lack of visual reference (caused by the VR user wearing a HMD), a lack of features in the bystander's oral description, or both, preventing collaboration between the VR user *insider* and the *outsiders*.

Taking as a starting point the overall vision that (1) IA and InfoVis/VA tools should synergize, (2) there is not a single tool or application to serve all data exploration purposes, and (3) collaboration between multiple users is desired, we are motivated to investigate a scenario that allows users outside the immersive environment, using non-immersive tools, to join the VR user in order to explore data together, receiving insights in asymmetrical collaborative IA according to the defined research focus (see Section 1.2). We believe the proposed scenario of hybrid asymmetrical collaboration between an immersed and a non-immersed user is relevant for several reasons. First, many studies focused around collaborative IA assume all collaborators use immersive technologies. Second, few studies to date have explored (remote) collaboration, as well as effects of using asymmetric technologies (for instance awareness, deixis, or group dynamics) within the context of IA [6]. Third, we present an applied real-world case study of IA within the context of the Digital Humanities.

3 HYBRID ASYMMETRIC COLLABORATIVE IMMERSIVE ANALYTICS SYSTEM

We propose a hybrid asymmetric collaborative immersive analysis system, consisting of an immersive VR application and a non-immersive web application, enabling synchronous data exploration by two (co-located) users. This section describes the data context, the immersive and non-immersive applications, and their collaborative features.[2]

3.1 Data Context and Scenario

We demonstrate our system in practice within the context of the Nordic Tweet Stream (NTS) corpus, a dynamic corpus of real world Twitter messages [32]. Besides the actual content of a tweet, usually in form of a text message, various metadata are attached, such as the geolocation from where a tweet was published and the language of the tweet. Over 50 metadata items for each tweet exist in the NTS, qualifying it as a multivariate dataset. The NTS corpus includes only tweets for which it could be determined that they originated in one of the five Nordic countries (Denmark, Finland, Iceland, Norway, or Sweden). Due to the diversity of the different metadata attributes, various possibilities for data exploration arise. For the purpose and scenario presented here, the focus is put on the geolocation and language. The developed system allows users to investigate the language[3] variability of the tweets and their hashtags within the Nordic countries from a sociolinguistic perspective, which is of particular relevance and interest for language researchers [2]. To prepare the data for interactive visualization within our system, certain preprocessing tasks were necessary. The partial NTS dataset we considered consists overall of 11,657,987 tweets, collected within the time period of November 6th, 2016, and February 26th, 2018. The number of tweets per day averages to 26,139. 1,452 unique locations and 188 unique languages (determined by each tweet's `lang` metadata value) have been identified.[4] The coordinates for each location are described as a bounding box, and the central longitude and latitude of each rectangle was calculated (as not all tweets included in the corpus contain an exact latitude and longitude). Using these unique and consistent coordinates for each location, we calculated the cluster centers for all the possible places. Using the R package *leaderCluster*[5], the 1,452 unique locations were compiled into 316 clusters with a radius of 60 km (utilizing the *haresine* distance metric). Having a lookup table of each place and the cluster it belongs to, enables us to allocate and aggregate the tweets that were published from each place and also represent the place clusters using their center latitude and longitude.[6]

3.2 Immersive VR Application

To explore the processed NTS corpus in an immersive environment, we developed a further iteration of our previous system, which allows open data exploration in VR [47] by extending it rigorously. We iterated on the prior design to reflect on the NTS context and scenario. Our immersive application is developed using *Unity3D* and centered around a room-scale VR setting, using a HMD (*HTC Vive*) as the user's display interface, and 3D gestural input (*Leap Motion*) as the interaction interface to operate the application (see Figure 1).

3.2.1 Visual Design. The five Nordic countries are rendered as color coded extruded surfaces on the floor. By displaying the countries this way, we intend to provide navigation and orientation cues to the VR users as they *walk around and explore the data*. Clusters are visualized as stacked cuboids,[7] positioned at their determined geolocation. Each node stack consists of four cuboids, where the top three represent the amount of tweets of the three most frequently used

[2]Video demonstration of the developed hybrid asymmetric collaborative immersive analysis system: vimeo.com/451482987.
[3]The language of each tweet as provided by the Twitter API, with no further processing.
[4]The vast majority of tweets were from the major urban areas, and only in a small subset of these unique languages.
[5]https://cran.r-project.org/web/packages/leaderCluster/index.html
[6]It would be impractical for IA purposes to visualize the individual data points not aggregated and clustered to a certain degree.
[7]These will be referred to as *nodes* in the rest of the text.

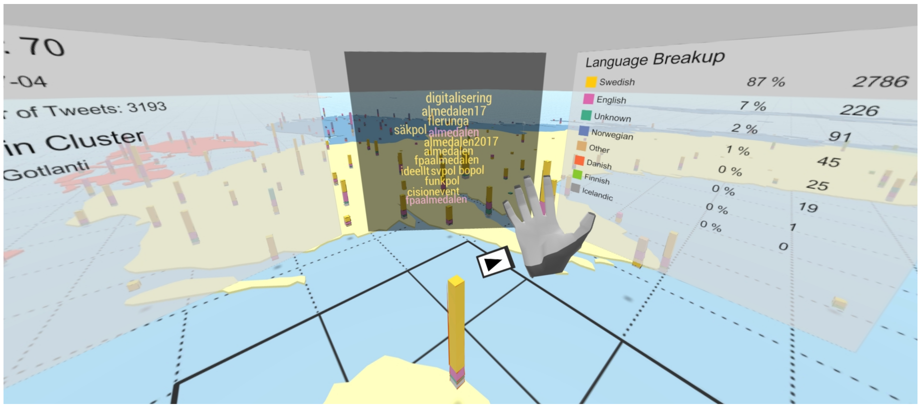

Fig. 1. The immersive VR application (see Section 3.2). Supplemental 360° interactive, annotated scenes of the VR application can be viewed online – vrxar.lnu.se/apps/2020-nordichi-hcia/.

languages, while the fourth one contains the remaining. All the individual cuboids are scaled in height, based on the amount of tweets they represent, and are color coded, e.g., yellow represents the Swedish language. The overall height of each node is scaled logarithmically[8] in order to reflect the total amount of tweets in that cluster. Thus, nodes with a high amount of Twitter traffic appear as taller stacks, while nodes with a low amount appear shorter. To display more information about a selected node, a three-panel window can be toggled. The center panel displays a precompiled tag cloud, featuring a preview of the most frequent hashtags detected in the tweets, also color coded based on the tweet's language. The detailed language distribution is displayed in the right panel as a list of languages along with their color, percentage, and absolute count of tweets. The left panel displays additional information, such as its identifier, the date of the data, the total number of tweets, as well as the unique names of all (real-world) locations contained in the cluster node (see Figure 1). The general motivation is for the user to be able to first get an *overview* of the data (observing the stacked cuboids), and then display *details-on-demand*, applying Shneiderman's [1996] overall design philosophy.

3.2.2 Interaction Design. 3D gestural input enables the user to interact within the VR environment while wearing the HMD. Both the user's left and right hand are simultaneously detected and visualized accordingly. Two techniques allow the user to select a node. Using *select-through-touch* the user can approach a node in close proximity by walking up to it and then simply touch it. Although the user is theoretically able to walk near infinitely within the virtual space, the physical real world boundaries limit their actual movement, thus requiring an alternative selection technique to select nodes outside the designated play area of the room-scale VR setup. Using *select-through-point* the user can gaze at a faraway node to highlight[9] it, and then, using an analogy of "*I want to go there*", make a *point forward* hand posture to initiate a target-based travel movement to the newly selected node. Once arrived at a distant node, the exploration of the new close-proximity nodes can continue. The selected node distinguishes it from all others by featuring a red outline as opposed to a black one. While the nodes are normally placed on the virtual floor (on top of the country surface) to provide the user with an appropriate visual perspective and overview, interacting with the nodes in close proximity would be rather cumbersome, as the user would need to reach down to the floor. Thus, to

[8]A logarithmic scale has been chosen in order to deal with the wide range of tweet frequencies within the different clusters for this dataset, as more populated areas may show several thousand tweets per day, while clusters in rural areas rarely show more than single- or double-digits.
[9]A highlighted node is temporarily increased in its size (scale) to provide a preview as far away nodes appear smaller (human visual perception [35]).

improve ergonomics, nodes near to the user are elevated to approximately each user's chest height, making them easily reachable for direct interaction. Elevated nodes cast a shadow to their direct geolocation on the (country) floor, maintaining their country affiliation even in areas close to borders. Using a *thumbs up* hand posture the user can toggle the display of the three-panel information window for the selected node, which will appear (and be anchored) at the user's head height and rotation (see Figure 1). To keep track and highlight a node that the user determines as interesting, a visible marker can be attached to it by *grabbing* the cluster and *pulling out a virtual pin* (see Figure 3). A one-buttoned play/pause menu is attached to the user's right hand palm (see Figure 1) to toggle the state of the VR application's gesture recognizer as active/inactive.[10]

3.3 Non-Immersive Web Application

Reading large amounts of text is still more convenient outside VR, using a normal computer monitor. Thus, in order to support detailed exploration of hashtags in tweets in regards to language variability, we implemented an interactive 2D information visualization using *D3.js* that runs in a web browser and can be operated through a normal desktop computer, notebook, and mobile device (see Figure 2). The core tasks for the exploration of the NTS data include browsing of detected hashtags in tweets of a given cluster and their sorting based on frequency and language.

3.4 Connectivity and Collaborative Features

Based on prior experience and observations as described in Section 2.3, the main goal of our system is to enable a pair of users to collaboratively explore the NTS corpus at the same time, one using the immersive, and the other the non-immersive application. Thus, additional features to facilitate and support collaboration are needed. At this initial stage, we focus on two important concepts within CSCW: (1) The users' mutual understanding of their exploration context (*Common Ground and Awareness*), and (2) their ability to make spatial references (*Reference and Deixis*) [26]. For that purpose, we implemented a real-time communication interface between both applications using *WebSockets*.

Position, orientation, and 90° field of view of the VR user are displayed within the web application's *Map View* (see Figure 2a). This enables the non-immersive application user to have at all times a spatial understanding of where the VR user is currently located, and what direction they are facing. Both the selected and the *pinned* nodes of the VR user are visually highlighted in the *Map View* of the non-immersive application. Similar to the *Web User Table View*, the non-immersive application features two interactive tables to present information about these nodes (see Figure 2c). This enables the non-immersed user to ad-hoc switch to the spatial references and context of the VR user. To provide the non-immersed user with the ability to make spatial references to *point* the VR user to a specific node, a large semi-transparent white pillar surrounds the node in the virtual space, easily recognizable, but not distracting, based on their *context-click* selection (see Figure 3). Marking the selection of the non-immersed user for the VR user may facilitate the guidance of the latter to the same place, allowing them to synchronize their contexts. The described and implemented features should support the users' oral communication[11] through the display of these additional information, particularly as the VR user (wearing a HMD) is unable to establish visual contact with the non-immersed user. Communication and the use of deictic terminology along the lines of "*look at the node behind you*" or "*have a look at that one*" under assistance of the provided features may facilitate a more direct exploration of both users.

[10]This provides the user with an opportunity to pause the gesture recognizer, for instance in situations when a longer passive observation in VR is desired, as the filtering of *unintentional gestures*, i.e., hand postures and gestures detected by the computing system even though the user did not intend to perform them, remains a known challenge of 3D gestural input [36].

[11]In our scenario, due to the co-location of both users, they are able to orally communicate with each other. A distributed scenario where both users are located in different physical locations, could be be implemented using real-time communication technologies.

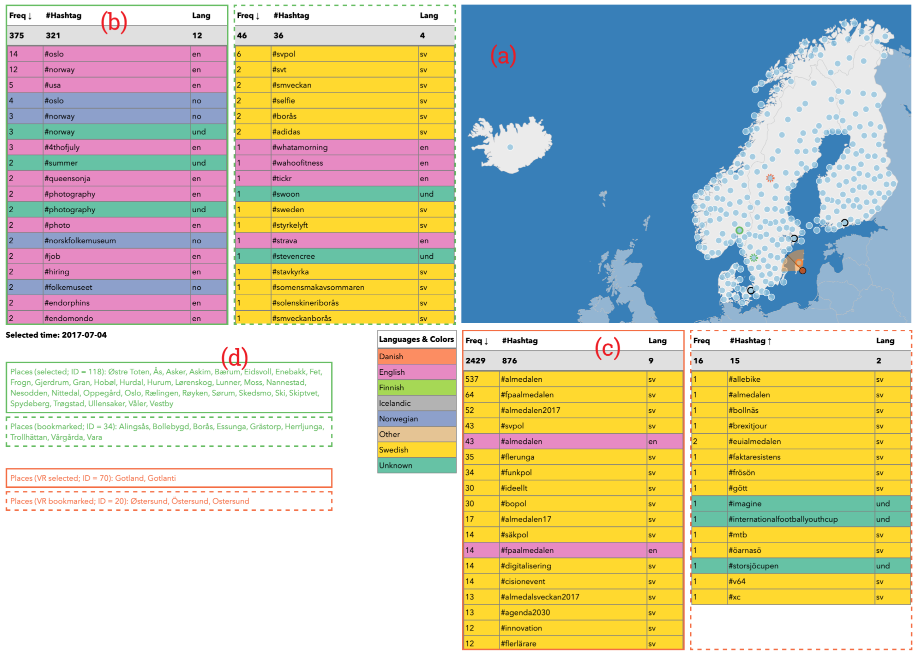

Fig. 2. The non-immersive application (see Section 3.3), consisting of several views that are interconnected, meaning that interactions in one view will cause others to update accordingly. The (a) *Map View* presents a geographic map of the Nordic region with all cluster nodes represented as circles. Using the pointer, each node can be selected by clicking on it. The user's selection is indicated by a green outline. The (b) *Web User Table View* consists of two tables. The bottom right corner contains a similar view (c) displaying the VR user's selections (further described in Section 3.4). Each table features three columns (in order): the *frequency* stating the total count of the hashtag; the *hashtag* itself; the *language* of the tweet the hashtag was detected in. Each column header can be clicked in order to sort its respective column ascending or descending. Using *click* and *context-click*, i.e., *left-* and *right-click*, the user can select two different nodes at a time, which will update the two table views accordingly. The (d) *Information View* displays additional information: the date of the explored data; the (real world) places in the selected clusters; a legend illustrating languages and their assigned colors.

We hope to satisfy multiple intentions with this first set of collaborative features. First, based on additional visual cues, we want to make the VR user more aware of what the non-immersed user is exploring, and vice versa. Second, due to the increased context awareness, we hope to ease their oral communication. Finally, due to the assisting visual cues and facilitated oral communication, we hope to increase both of the users' engagement within the collaborative data exploration task, enabling them to make sense of the data together as well as increasing their individual understanding of the data, while both users operate tools with different purposes to explore the same data.

4 EVALUATION METHODOLOGY

4.1 Use Case Classification

Regarding the possible use cases of our system, we propose the classification illustrated in Figure 4. It consists of two continuous dimensions. The first dimensions is defined by whether just a partial or a complete (as much as possible) exploration of the dataset is required by the defined task. The second dimension reflects the most efficient (or desired) manner of collaboration during the sessions, ranging from working closely together to being rather independent most of the time. Using this classification, we can not only define use cases (such as the ones shown in Figure 4), but also

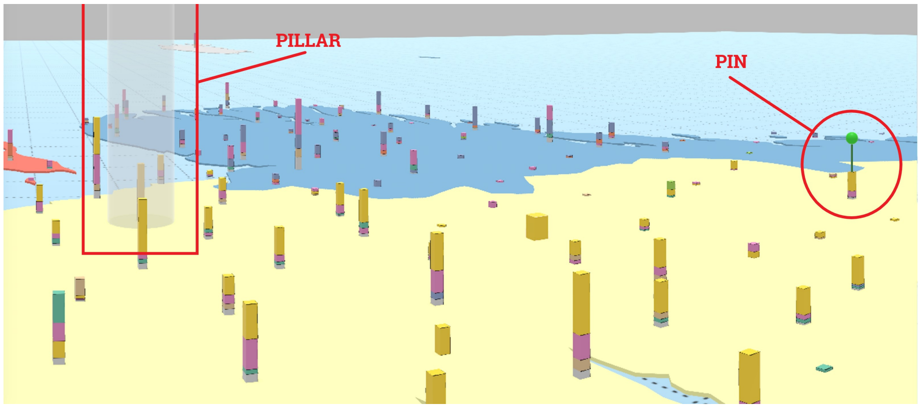

Fig. 3. Collaborative features as seen in the immersive VR application (see Section 3.4). The semi-transparent white pillar represents the non-immersive user's pointer, while the pin represents a pointer made by the immersive application's user.

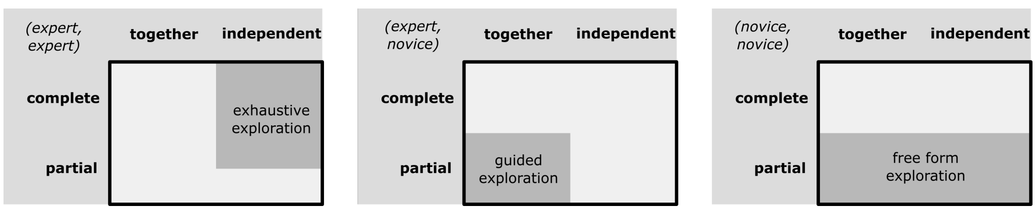

Fig. 4. The two continuous dimensions for our classification are: whether the users collaborate in a mostly *together* or *independent* manner, and whether the task involves a *complete* or *partial* dataset exploration. We consider three possible use cases for our system: (left) exhaustive exploration involving only experts, (center) guided exploration involving both experts and novices, and (right) free form exploration involving only novices.

characterize what kind of collaborative activity took place during a session, and whether this was according to what was expected. For example, in the study presented in this section, the tasks were designed as *free form exploration*, as they involved only novices. The NTS corpus was expected to be only *partially* explored (due to time limitations, among other factors), and both *together* and *independent* styles of collaboration were desired. This use case is shown in Figure 4, right. Another use case, would involve a more guided/teaching scenario, where one of the users in each session would be a language teacher (expert) along with a language student (novice). Such a scenario would require them to collaborate closely *together*, and it makes sense to only focus on a *partial* aspect of the dataset (see Figure 4, center). Furthermore, having only language researchers (experts) using the system is yet another scenario (see Figure 4, left). Given their expertise, it makes more sense that they collaborate mostly *independently* (while of course coming together every now and then) rather than working together all the time. In that distributed way, a more *complete* exploration of the dataset might be possible.

4.2 User Interaction Study

The study was conducted with pairs of participants that alternated the roles of one person being immersed in VR, and the other using the non-immersive web application.

4.2.1 Setup and Environment. All sessions were conducted in our research group lab, which features a square two-by-two meters area, designated for a VR user to move free of obstacles. Additionally, it features a workbench consisting of a table, a chair, and a computer, for the user operating the non-immersive web application. Our lab provides enough space for two participants as well as two researchers to conduct such an experiment comfortable and uninterrupted.

4.2.2 Tasks. Each pair of participants was asked to collaborate in order to perform tasks within a sociolinguistic context. We defined two tasks, asking the participants to make respective assessments regarding (1) the language distribution of tweets (comparing regional and others), and (2) how closely the distribution of the hashtags' language matches the distribution of the tweets' language (for each region). The tasks were designed from a perspective of *explorative analysis*, i.e., undirected search with no hypotheses given [1, Ch. 1] [53, Ch. 1]. The participants were asked to combine their observations regarding both of the above into a final reasoning for the selected region(s). For the purpose of the study, we selected two dates in the year 2017 within the NTS corpus data: May 23rd as dataset A, and October 21st as dataset B.[12] The order the datasets were presented was random, and the participant roles would switch between the tasks. The task was designed to encourage an open exploration of the dataset by the participants using their own strategy and pace.

4.2.3 Study Procedure. One week prior to the user study, a class of first-year language students was provided with an overall introduction of the developed system by showing them a video that demonstrated the main functionalities of both applications (they were not shown any examples of use). This ensured that all participants received the same introduction. Each study session followed the same procedure of four stages: (1) welcome; (2) first task; (3) second task; (4) semi-structured interview and goodbye. Each of the two task stages was planned to go on for approximately ten minutes, keeping the overall session (including warm-up, filling in forms, interview) under one hour.[13] In the first stage, the two participants were welcomed and asked to fill in a user consent form. Each task completion stage featured a warm-up phase,[14] completing the task together with the other participant, and finally filling in a usability questionnaire for the application they operated. After the first task, the dataset and participant roles were switched accordingly. Finally, a semi-structured interview with both participants concluded the study.

4.3 Data Collection

We used a mixture of quantitative and qualitative methods to collect data. The System Usability Scale (SUS) questionnaire was used to gain insights about usability aspects for each of the two developed applications [4, 9] (see Section 5.1). A logging system implemented in each application enabled a comprehensive user input collection. Each log entry features a `timestamp`, the performed `action`, the `object` that performed the action, as well as the `target` that the action was performed to (see Section 5.2). Two researchers observed the participants, taking notes about their communication and interactions with the system as well as with each other, to collect further empirical evidence (see Section 5.3). The participants were encouraged to *think aloud*, enabling the researchers to take notes of these oral communications as the participants spoke to each other (see Section 5.4). Finally, a semi-structured interview with both participants was conducted (see Section 5.5).

[12] The birthdays of Carl Linnæus and Alfred Nobel, respectively.
[13] The time spent immersed in VR per user was estimated to approximately 15 minutes, i.e., five minutes warm-up and ten minutes task completion.
[14] The warm-up phase provided each participant with the opportunity to become familiar with their respective application. The participants were presented with data from July 4th, 2017 to ensure they would not take over any insights to their actual tasks.

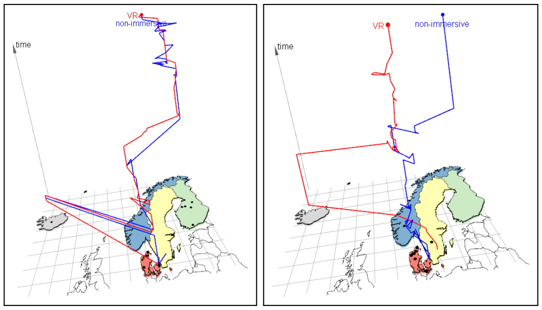

Fig. 5. Visualization of user trajectories through the data space, based on system logs. Two examples where participants collaborated: mostly *together* (left), and in an *independent* manner (right; the VR user went to Iceland, while the non-immersed user focused mostly on Denmark). These correspond to the first task of sessions 1 and 7 (see Tables 1 and 2). An interactive version can be viewed online: Left – vrxar.lnu.se/apps/2020-nordichi-hcia/fig6-left.html; Right – vrxar.lnu.se/apps/2020-nordichi-hcia/fig6-right.html.

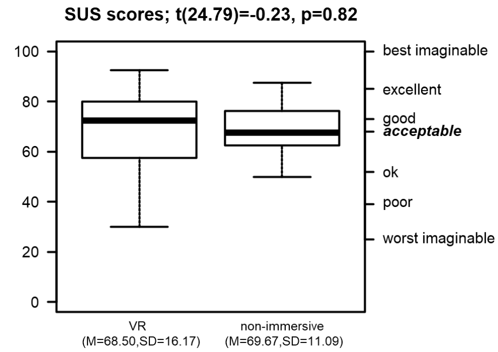

Fig. 6. SUS scores for VR and non-immersive web app. Right axis adjective ratings based on Figure 4 from [4]. An independent samples t-test was conducted to compare the two conditions' mean SUS score. There was no statistically significant difference for the VR ($M = 68.5$, $SD = 16.17$) and non-immersive application ($M = 69.67$, $SD = 11.09$) conditions; $t(24.79) = -0.23$, $p > .05$. Samples were tested for normality using the Shapiro-Wilk test.

5 EVALUATION RESULTS

A user interaction study with $n = 15$ participants[15] was conducted. First-year bachelor language students, none of them having prior experiences with the developed system or VR in general, paired up for a total of eight sessions.

5.1 System Usability Scale (SUS)

The SUS scores for the VR and the non-immersive application are presented in Figure 6. The mean values for both are slightly above the *acceptable* threshold (i.e., score > 68, see discussion in [9]).

5.2 System Logs

Using the system logs, we are able to reconstruct the collaborative behavior of the pairs, as visualization of the trajectories of both VR and non-immersed users within the data space. Based on our classification presented in Section 4.1, we confirmed that our participant pairs explored only parts of the corpus (due to the set time limitations), and collaborated using both *together* and *individual* styles; Figure 5 shows two representative examples of these styles. Regarding the use of the connectivity and collaborative features described in Section 3.4, Table 1 shows that overall, both VR and non-immersive users *highlighted* specific nodes that were then explored by their partner. In some cases, these features were used more than in others, but these *deictic gestures* were to a great extent acknowledged, and benefited the collaboration.

5.3 Task Assessments

Free to choose their own exploration strategy, each pair was able to make assessments in regards to the given task. Table 2 provides an overview of their assessments and what countries they chose to explore during their two tasks.[16]

[15]Due to a last minute cancellation, a doctoral student in linguistics was recruited as a substitution. His data are excluded from the analysis.
[16]Note that the ten minutes limit per task proved insufficient for making assessments for all five countries; instead, participants mostly focused on different ones across the two tasks, and provided a Nordic overview over the entire session.

Session	VR user $nodes_{mark}$ ($nodes_{explore}$)	Non-immersed user $nodes_{mark}$ ($nodes_{explore}$)
1	8 (8)	10 (10)
	4 (4)	15 (14)
2	0	12 (10)
	1 (1)	5 (3)
3	1 (0)	3 (3)
	1 (1)	1 (1)
4	2 (2)	*substitute participant*
	substitute participant	4 (2)
5	0	1 (1)
	2 (2)	3 (1)
6	1 (1)	7 (5)
	4 (3)	4 (3)
7	5 (5)	13 (5)
	3 (3)	20 (13)
8	6 (4)	5 (5)
	7 (6)	5 (5)

Table 1. For the first and second tasks of each session, the number of nodes *marked* by each user (see Section 3.4) and how many of those were consequently *explored* by their partner.

Session	Assessed countries First task	Second task
1	DK, FI	SE, NO, IS
2	DK, IS, NO	SE, FI
3	SE	DK, IS
4	IC, NO, DK	FI
5	SE, FI	SE, NO, IC, DK
6	SE	DK, NO
7	IC, DK	FI, SE
8	DK, SE	NO, FI

Table 2. Participants' assessments per study and task session. The countries' order reflects the order the participants chose to explore the data and provided their assessments.

Exploring Denmark, the students discovered that the use of English and Danish language in tweets (and hashtags) was rather equally distributed, with some increased frequency of Danish towards the countryside ("*Maybe farmers?*", according to one pair). Students were surprised by how dominant and "*omni-present*" the use of Finnish language was across the entirety of Finland, with English language appearing only in more populated places; they also noted the low frequency of Swedish in Finnish tweets. This observation was declared as quite different from those of other countries, initiating thoughts such as, "*The Fins really want to use it* [the Finnish language] *to prevent it from going away*". The students were intrigued with their Iceland observations, stating that both English and Icelandic language were quite equally used in tweets, but more hashtags were attached to English tweets. Investigating those hashtags, the students concluded that tourism may be a reason. Exploring Norway, the students found that the majority of hashtags attached to tweets were in Norwegian rather than English, even though there seemed to be quite some English traffic along the coasts (attributed to "*tourists visiting the fjords*"). Sweden's exploration was more versatile, as students highlighted some differences between the south (fairly uneven distribution of hashtags and languages) and the more center and northern parts (more Finnish language towards the border to Finland; lots of tweets discovered in *other* languages, while hashtags were rather attached to Swedish and English tweets). The students also discovered that the use of Swedish was dominant in the metropolitan areas both in terms of language and hashtag usage. Similar to Norway, some students assessed that a fair amount of the hashtags themselves were in Swedish.

5.4 Observations

The notes of the two observers were combined, coded, and examined in order to identify reoccurring patterns. For the purpose of the reporting here, we refer to *sessions* and *tasks*: *session* indicates that the phenomena were observed in both tasks, while *task* indicates an occurrence in only one of the two tasks for an individual pair.

Three pairs approached their task solving noticeably systematical and structured throughout their session, engaging in frequent oral communication and discussions to provide informed assessments. Three pairs appeared to explore the data closely together, unconnected to whether they approached the task completion systematically or not. A pair exploring individually and in silence was noticed only during one task. In terms of the decision making of where to explore next, a rather equal distribution between guidance through the VR user and guidance through the non-immersed user was noticed during three tasks. The VR user guiding the non-immersed user was observed in one task, while the non-immersed user clearly guided the VR user in four tasks. The use of deictic references and related terminology was explicitly observed throughout four sessions and two tasks, and included phrases, such as "*I am here*", "*Let's look there*", "*Do you want to to go there?*", "*Go here*", "*Let's finish here first*", "*Where do you want me to go now?*", "*Do you see this/that?*", "*Have you seen this one?*", "*Where do you want to go? Select a place, and I will go there*", "*Come here*", "*Turn around*", "*Behind you*", "*Next to you*", "*Should I come to you?*", "*Look at this one, I pinned another one*", "*I pinned this one here*", and "*This is quite interesting! Look at this one*". During one session and one task, one member of the pair appeared more dominating (by personality) in regards to their team work compared to the other one. Within one session and three tasks, the pairs made heavy use of their contextual and prior knowledge, discussing and commenting on certain phenomena they discovered within the data, covering a variety of topics, such as for instance anecdotes about places the participants had visited in real life, or about major news events that significantly influenced the Twitter hashtags on the task dates. The use of the collaborative features, particular in terms of the users' mutual ability to create spatial references by *pointing* in the data, was heavily observed during five sessions and three tasks (see also Table 1). Participants in three sessions gave active verbal acknowledgements that the display of the VR user's position and orientation in the web application supported their understanding and awareness of the VR user's context. During one session and three tasks, the VR user was observed actively commenting on the underlying map in the virtual 3D environment and, in conjunction, their ability to navigate and orient themselves in the geospatial dimension based on geographical knowledge. Visible and audible indications of a generally pleasant experience, for instance noticeable fun and laughter, were observed during four sessions and two tasks. Six participants appeared to be immediately very fluent with the interaction in the virtual 3D environment. Some additional initial efforts, e.g., to learn the VR application's *thumbs up* hand posture to view more information about a node, were observed with six participants.

5.5 Semi-Structured Interview

In a joint interview with both participants at the end, they were asked whether they considered the roles of the two applications evenly balanced. Additionally, they were asked to consider a hypothetical scenario where they would only be allowed to use one of the applications to explore the data, and whether they would have a preference regarding the use of the immersive or the non-immersive application, given that each application satisfies different exploration purposes. Four participants expressed the opinion that the balance between the VR and web application user's role was rather equal. Six participants favored the VR application over the web application, while one participant preferred the web application. Four participants stated that their answer regarding preference would depend on the task or the goal of the activity, thus not being able to decide whether they would favor VR or the web application. However, five participants actively argued that they would prefer a collaborative scenario as experienced within the user study, regardless of their answer whether they prefer VR or the non-immersive application. Six participants could not give a clear preference of one application over the other. The participants also provided some further general comments. Six participants emphasized that the immersive VR application allowed them to get a good overview of the data. Six participants stated that the non-immersive web application featured a lot of details. Eight participants actively acknowledged experiencing a learning effect in their collaboration and interaction between the first and second task. One pair genuinely appreciated their experience, stating that it felt like "*a two-person job*". Another pair acknowledged the feeling of time passing by rather quickly due to their engagement in the joint data exploration. Another pair highlighted that, "*It was so much fun to have both applications, especially for the* [non-immersed] *user, otherwise it would be rather dull.*" Two pairs emphasized that they did not feel any barrier within the oral communication, enabling them to naturally speak and interact with each other using the provided features, self-reporting their perceived coordination and collaboration as "*good and easy*".

5.6 Limitations

Considering the number of participants, the results present trends and indications that are to be interpreted in regard to the presented context and target group. Limitations inherent to the chosen methodology and data collection methods are to be taken into account (e.g., subjectivity of the researcher's observations, self-reporting nature inherent of the questionnaire completion through the participants). Finally, the nature of task within the context of CSCW required the participants to collaborate within one another, presenting them with a demand for social processes, that are inherently dynamic and may vary themselves.

6 SUMMARY AND DISCUSSION

We set out to investigate interaction and collaboration between a user *inside* VR and a user *outside* the immersive environment within the context of IA to bridge the gap between user-centered experiences and collaborative data analysis. We highlighted relevant research challenges, and reviewed related work within the context of IA and CSCW, as well as in regards to immersive interaction and collaboration. Based on these insights and prior real world observations, we described our motivation, and implemented an immersive VR and a non-immersive web application that are connected in real-time to support the collaboration between the users, in particular towards their ability to make (spatial) references and awareness of each other while orally discussing the data. In a real world case study, pairs of language students used the implemented applications to investigate a large Twitter corpus from a sociolinguistic perspective within an explorative analysis scenario to get insights about the usage of language and hashtags within the Nordic region. This case study allowed us to investigate the system's usability and to validate the overall approach.

Usability. The reported SUS scores for both applications (see Section 5.1) point towards an *acceptable* usability for both, generally indicating that the participants were able to operate them. Thus, one may infer that the whole system (consisting of both applications) is indeed usable within the presented IA context. Some of the reported lower SUS scores for the VR application may be attributed to the observed initial difficulty of learning the 3D gestural input (see Section 5.4). However, given that it was each user's first interaction with the VR application, and the rather short exposure time in the immersive environment (approximately 10 to 15 minutes including warm-up), it is noteworthy that all of them *learned* to utilize its features and explore the data accordingly. Further usability aspects, for instance what 3D gestural input to use for specific data interaction tasks, may be subject of future investigations.

Collaboration. The developed system features characteristics of remote collaboration, even though the collaborators were co-located in the same physical space and able to orally communicate with each other. However, they were not able to rely on important collaborative information cues due to the nature of the set up and technologies involved. Consequently, we were interested in how the users would approach their collaborative data exploration using the provided features. Based on the log files, observations, and interviews (see Sections 5.2, 5.4, and 5.5), we consider the results promising in various regards. First, the students appeared very engaged in the activity itself as well as in the collaboration with their peers. In most of the cases, their oral communication was frequent and natural, using a fair amount of close collaboration in order to explore the data together using the two applications for their designated purposes. It was particularly interesting to listen to their choice of words, commonly making use of *deictic* terms and expressions, in combination with the *referencing* abilities as provided through both applications in order to synchronize their context and understanding of where they are having to look at together. Generally, the collaboration between all the students felt (subjectively) organic. While some pairs approached the tasks rather enthusiastically and actively (some of them even continued with minor exploration endeavours after the tasks were completed), a few appeared to be rather shy and conservative at first. We believe that this is simply due to the personalities of the participants, both individually as well as collectively, particularly in regards to Churchill and Snowdon's [14] acknowledgement, who state "*(...) that cooperative and collaborative activities involve considerable negotiation, and teams vary tremendously in their negotiation strategies as well as in their task accomplishment process*". Second, it was particularly interesting to investigate how the students would make use of the provided collaborative features. The detailed display of the VR user's position, orientation, and selection live in the web application's interface enabled a user to be aware of the VR user's context (subjectively) at all times, arguably providing a *monitoring* tool. Often the non-immersed user orally acknowledged their awareness of the VR user's exploration context. This allowed the VR user, visually immersed, to focus on the exploration of the virtual 3D space. However, the web user often used the provided *pointing* feature, guiding the attention of the VR user ad-hoc to highlighted POIs in the virtual environment. Arguably, the non-immersed user had more (visual) awareness of the VR user. In most of the cases, the VR user found something of interest and simply stated (along the lines of) "*look what I found*" or "*look where I am*", and the web user was able to do so. This can explain the relatively lower use of the collaborative features by the VR users (see Table 1). Third, all pairs were able to complete the tasks and make a variety of observations within the given scenario (see Section 5.3). One of the two observing researchers, a domain expert within linguistics, was satisfied with the participants' answers, rating them as reasonable and along the lines of what is expected of first-year students in terms of complexity and critical thinking. Furthermore, it was nice to see that the students' dialog with each other encouraged them to base some of the assessments on meta information, e.g., their own contextual knowledge.

Conclusion. The main outcomes of the presented work is a proposal of a novel way for asymmetrical collaboration within the context of IA. Using the insights gained from the conducted real world use case we consider the general approach validated in terms of usability. The participants were excited to use the system for their collaboration, the VR application providing an immersive take on data exploration, while the non-immersive application allowed the user *outside* the VR environment to participate in an inclusive and meaningful way. The system allowed its users to approach the task in a rather flexible way, choosing their own exploration strategies. Importantly for future applications, the interactions between the immersed and the non-immersed user fostered experiences of shared discovery, which has great potential for group work scenarios of data exploration tasks and educational contexts, especially in higher education where students are increasingly introduced to the large datasets produced in humanities scholarship today.

6.1 Future Work

Based on these first insights, there are several directions for future research. For instance, more design recommendations are needed in regard to the application of 3D gestural input for typical operations in immersive VR environments within the context of IA–not just within the scope of our presented application, but in general. Further studies, examining particularly the collaborative and communicative behavior of the co-workers within the presented scenario (one *inside* and one *outside* VR), are likely to lead to interesting findings as well, e.g., in user engagement, their attention, and empathy. The application of the presented scenario using different datasets, either within the linguistics domain or one completely different, keeping a similar explorative data analysis setting, offers itself naturally for further research.

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