Exploring Relationships among Topics in Neuroscience Literature using Augmented Reality Visualization

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Life is our stage for a one-time performance
Each sings their song and exits
The stage always remains
Blessed is the song that stays in people's memories

Mastaneh Soltani

Cover design by Ghazaleh Tanhaei. The cover combines traditional Iranian painting styles with the thesis topic. It depicts Shahrzad, an Iranian woman, wearing an augmented reality headset to view a virtual brain.

The research for this dissertation was conducted at the DatAR group, part of the Department of Information and Computing Sciences (ICS), Faculty of Science, Utrecht University, the Netherlands.

Exploring Relationships among Topics in Neuroscience Literature using Augmented Reality Visualization

Onderzoek naar relaties tussen onderwerpen in de neurowetenschappelijke literatuur met behulp van Augmented Reality-visualisatie

(met een samenvatting in het Nederlands)

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Contents

Abstract

Neuroscience researchers regularly sift through the literature for various goals. One of their main goals is to identify options for new experiments they want to carry out. To achieve this, Neuroscientists must understand known relationships between topics such as mental processes, brain regions, and brain diseases. A neuroscience experiment to verify any specific relationship is costly and time-consuming. Therefore, it is critical to precisely identify experiments that have the greatest potential for contributing knowledge to the field. For example, a specific relationship reported in only very few publications may indicate a lack of experimental evidence rather than a lack of any causal connection.

We claim that visualizing existing knowledge from neuroscience literature with Augmented Reality (AR) can assist neuroscience researchers in identifying existing or potential relationships that are fruitful to explore in scientific experiments. To prove this claim, we conducted a series of three user-centered design studies with 3D visualizations in AR for different exploratory tasks.

To do this, we developed a prototype immersive AR system called "DatAR" that was used as the basis for the experiments.

- In the first study, we investigated potential representative neuroscience literature exploration tasks and appropriate visualizations to support these. We demonstrated an early version of our DatAR prototype in sessions with eight neuroscience students. After carrying out a specified relationship-finding task, they could explore the implemented functionality and visualizations. Through interviews, we validated the relationship-finding idea implemented in the prototype and the visualizations of the relationships. As a next step, we added functionality to see the sentences and references associated with a selected relationship between a specific disease and a specific region. At that time, both directions were supported; from a specific disease to all related regions and from a specific region to all related diseases. The evaluation was carried out by experts in general literature research. The result of the qualitative evaluation showed that the relationship-finding functionality implemented in the DatAR prototype was meaningful and explainable and the 3D visualizations helped participants to understand the relationships between neuroscience topics. This provides the first evidence that AR visualizations can help identify potential relationships for fruitful experiments.
- An interesting observation from our first two studies was that neuroscientists frequently want to know how two diseases affect the same regions of the brain. For a comparative analysis, the results for both diseases must be presented at the same time. In our third study, we therefore investigated how AR visualiza-

tions can assist neuroscientists in comparing brain regions affected by different brain diseases. We provided 3D models of the brain that emphasized the regions affected by these diseases to facilitate this comparison. We confirmed that using a 3D AR environment offers an intuitive visualization of brain regions affected by specific diseases. We verified that they enhance neuroscientists' comprehension by allowing them to explore the topics for patterns and relationships. Participants were able to identify a small number of papers to read to gain an in-depth understanding without the need to review an extensive number of publications.

- In the preceding studies, we evaluated each functionality developed as a separate widget. This concluding study investigated how the functionalities together can support neuroscience research. We identified representative tasks and scenarios through discussions with three neuroscientists. The scenarios support neuroscientists by using most of the developed widgets in a coordinated way. The results showed that the set of used widgets to understand relationships between brain-related topics could especially be useful for new researchers in neuroscience when they know little about the field. We also verified that widgets can support each other to visualize and verify results. The visualization of relationships was valuable and participants agreed that supporting other brain-related topics such as mental processes or cognitive function can increase the value.

Our findings provide a solid set of initial steps toward understanding how AR can be utilized to grasp the complex relationships among neuroscience topics. Altogether, these studies have demonstrated that an immersive AR environment can effectively display topics and their interconnections, facilitating the exploration of neuroscience literature.

Ghazaleh Tanhaei
Utrecht, August 2024

Samenvatting

Neurowetenschappelijke onderzoekers doorzoeken regelmatig de literatuur met verschillende doelen. Een van hun belangrijkste doelen is om opties te identificeren voor nieuwe experimenten die ze willen uitvoeren. Om dit te bereiken, moeten neurowetenschappers bekende relaties tussen onderwerpen zoals mentale processen, hersengebieden en hersenziekten begrijpen. Een neurowetenschappelijk experiment om een specifieke relatie te verifiëren is kostbaar en tijdrovend. Daarom is het cruciaal om nauwkeurig die experimenten te identificeren die de grootste potentie hebben om kennis aan het veld toe te voegen. Bijvoorbeeld, een specifieke relatie die slechts in zeer weinig publicaties wordt vermeld, kan wijzen op een gebrek aan experimenteel bewijs in plaats van een gebrek aan een causaal verband.

We stellen dat het visualiseren van bestaande kennis uit neurowetenschappelijke literatuur met Augmented Reality (AR) neurowetenschappelijke onderzoekers kan helpen bij het identificeren van bestaande of potentiële relaties die vruchtbaar zijn om te verkennen in wetenschappelijke experimenten. Om deze bewering te bewijzen, voerden we een reeks van drie op gebruikers gerichte ontwerpstudies uit met 3D-visualisaties in AR voor verschillende verkennende taken.

Hiervoor ontwikkelden we een prototype immersief AR-systeem genaamd "DatAR" dat als basis werd gebruikt voor de experimenten.

- In de eerste studie onderzochten we potentiële representatieve taken voor het verkennen van neurowetenschappelijke literatuur en geschikte visualisaties om deze te ondersteunen. We demonstreerden een vroege versie van ons DatAR-prototype in sessies met acht neurowetenschappelijke studenten. Na het uitvoeren van een gespecificeerde taak voor het vinden van relaties, konden zij de geïmplementeerde functionaliteit en visualisaties verkennen. Door interviews valideerden we het idee van het vinden van relaties geïmplementeerd in het prototype en de visualisaties van de relaties. Als volgende stap voegden we functionaliteit toe om de zinnen en referenties te zien die geassocieerd zijn met een geselecteerde relatie tussen een specifieke ziekte en een specifiek gebied. Op dat moment werden beide richtingen ondersteund; van een specifieke ziekte naar alle gerelateerde gebieden en van een specifiek gebied naar alle gerelateerde ziekten. De evaluatie werd uitgevoerd door experts in algemeen literatuuronderzoek. Het resultaat van de kwalitatieve evaluatie toonde aan dat de functionaliteit voor het vinden van relaties in het DatAR-prototype zinvol en uitlegbaar was en dat de 3D-visualisaties de deelnemers hielpen de relaties tussen neurowetenschappelijke onderwerpen te begrijpen. Dit levert het eerste bewijs dat AR-visualisaties kunnen helpen bij het identificeren van potentiële relaties voor vruchtbare experimenten.

- Een interessante waarneming uit onze eerste twee studies was dat neurowetenschappers vaak willen weten hoe twee ziekten dezelfde hersengebieden beïnvloeden. Voor een vergelijkende analyse moeten de resultaten voor beide ziekten tegelijk worden gepresenteerd. In onze derde studie onderzochten we daarom hoe AR-visualisaties neurowetenschappers kunnen assisteren bij het vergelijken van hersengebieden die door verschillende hersenziekten worden beïnvloed. We voorzagen 3D-modellen van de hersenen die de getroffen gebieden benadrukten om deze vergelijking te vergemakkelijken. We bevestigden dat het gebruik van een 3D AR-omgeving een intuïtieve visualisatie biedt van hersengebieden die door specifieke ziekten worden aangetast. We verifieerden dat ze het begrip van neurowetenschappers verbeteren door hen in staat te stellen de onderwerpen te verkennen op patronen en relaties. Deelnemers konden een klein aantal papers identificeren om te lezen om een diepgaand begrip te verkrijgen zonder dat ze een uitgebreid aantal publicaties hoefden te beoordelen.
- In de voorafgaande studies evalueerden we elke ontwikkelde functionaliteit als een aparte widget. Deze afsluitende studie onderzocht hoe de functionaliteiten samen neurowetenschappelijk onderzoek kunnen ondersteunen. We identificeerden representatieve taken en scenario's door discussies met drie neurowetenschappers. De scenario's ondersteunen neurowetenschappers door gebruik te maken van de meeste ontwikkelde widgets op een gecoördineerde manier. De resultaten toonden aan dat de set gebruikte widgets om relaties tussen hersengerelateerde onderwerpen te begrijpen vooral nuttig kan zijn voor nieuwe onderzoekers in de neurowetenschappen wanneer zij weinig over het veld weten. We verifieerden ook dat widgets elkaar kunnen ondersteunen om resultaten te visualiseren en te verifiëren. De visualisatie van relaties was waardevol en deelnemers waren het erover eens dat het ondersteunen van andere hersengerelateerde onderwerpen zoals mentale processen of cognitieve functie de waarde kan vergroten.

Onze bevindingen bieden een solide reeks eerste stappen naar het begrijpen hoe AR kan worden gebruikt om de complexe relaties tussen neurowetenschappelijke onderwerpen te begrijpen. Al met al hebben deze studies aangetoond dat een immersieve AR-omgeving effectief onderwerpen en hun onderlinge verbindingen kan weergeven, waardoor de verkenning van neurowetenschappelijke literatuur wordt vergemakkelijkt.

1

Introduction

Analyzing a vast number of publications in neuroscience research is essential to identify the most promising experiments that can provide new insights about relationships between brain topics. This is particularly important in neuroscience where experiments are often very expensive and time-consuming. However, reviewing such a large volume of literature leads to challenges. This process is both slow and carries the risk of overlooking evidence for potential relationships. Consequently, neuroscientists may struggle to determine whether the absence of these relationships is due to a lack of scientific evidence or causality.

Literature-based exploration limits researchers to the specific perspective contained inside each study, potentially missing broader, related patterns that can be seen only through analysis of the relationships among the neuroscience topics described in the publications. This may hinder the synthesis of new ideas by limiting the perception of neuroscience's complex nature. We postulated that exploring the literature through topics could be a potential means of providing an informative overview. This allowed for analyzing the relationships between different neuroscience topics rather than the individual publications. We hypothesized that the relationships found in this way would help neuroscientists more easily identify an experiment with the greatest potential for novel findings.

To visualize the identified relationships between topics, given the three-dimensional nature of the brain, we propose that employing Augmented Reality (AR) to visualize neuroscience topics could improve the exploration of the relationships among them, thus improving current ways of analyzing the literature. By combining digital information in the real world, AR allows users to engage with literature in interactive and immersive learning experiences. This environment not only facilitates a deeper understanding of complex relationships within the topics but also encourages users to think outside the box [1]. The AR visualizations enable users to manipulate and explore data in three-dimensional space, offering a more holistic view. This holistic view aids in recognizing patterns, relationships, and details that might be missed in traditional two-dimensional representations, leading to more thorough and informed analyses [2]. Consider the field of neuroscience, where neuroscientists could use such 3D visualizations to identify brain disease topics that are semantically similar by detecting their 3D location. Additionally, the immersive experience of AR can stimulate creativity and foster innovative ways of thinking, leading to more effective problem-solving and discovery in literature exploration [3].

With a User-Centered Design (UCD) approach, we identify literature exploration tasks that can benefit from an overview of the relationships among topics in neuroscience literature. We then design and evaluate a number of functionalities to support one or more of these tasks. For example, consider a neuroscientist reviewing the literature to decide on an experiment to conduct. By visualizing regions in a 3D brain model, neuroscientists are able to explore relationships and patterns between brain regions and brain diseases based on large numbers of published papers. As neuroscientists explore these relationships and patterns they are potentially able to identify new relationships for further exploration (e.g. by investigating why certain brain regions are associated with Depression but not Anxiety).

We present three main studies, and report on ten research questions (see sections 1.3.1, 1.3.2, and 1.3.3) that investigate the functionalities we develop for their usefulness, their usability, and the explainability of the corresponding visualizations in supporting neuroscience literature exploration tasks. Our overall goal is to facilitate a more intuitive understanding of the relationships among brain-related topics, ultimately contributing to the acceleration of identifying useful experiments in neuroscience.

1.1. Neuroscience Topic Repository

To allow researchers to explore neuroscience literature based on topics in our experiments we need to provide access to an analysis of literature. The online resource PubMed[1] provides access to the titles and abstracts of more than ten thousand neuroscience publications. We used two resources, Linked-Brain-Data[2] and Knowledge Graphs of Brain Science[3], which contain the co-occurrences of two topics in the same sentence, such as the Hippocampus, a brain region, and Alzheimer's, a disease. The repositories are constructed by counting the number of sentences that contain two topics, for example, "However, the Hippocampus is one of the brain areas affected by Alzheimer's (AD)" from the "Hippocampus and its involvement in Alzheimer's disease: a review" [4]. For each study we conducted, we will provide more details about the repositories used in subsequent chapters.

[1] `https://pubmed.ncbi.nlm.nih.gov/`

[2] LBD is developed and maintained by the Cognitive Brain Modeling Group at Institute of Automation, Chinese Academy of Sciences, China.

[3] Knowledge Representation & Reasoning (KR&R) research group at the VU, The Netherlands.

1.2. Providing Relationship-Finding Functionality in the DatAR prototype

We have developed several functionalities in the DatAR prototype during this research to facilitate literature-based exploration in AR. We have tested and improved the functionalities we developed for specific user tasks. The functionalities support different aspects of relationship-finding tasks and are implemented in the form of AR widgets in Unity. The widgets support the selection, querying, and visualization of results, allowing users to browse the neuroscience repository by topic.

A core of DatAR is the 3D brain model, Figure 1.1 - part A, based on the 3D positions of 274 brain regions provided by the Scalable Brain Atlas database. The second main visualization is the topic model of diseases, Figure 1.1 - part B, which maps 107 brain diseases in a 3D space, arranging them in such a way that the distance between any two diseases reflects their semantic similarity. This similarity reflected how often the diseases were mentioned with other topics, such as brain regions or genes, in the same sentence in the literature repository. The topic model visualization positioned semantically similar — and therefore potentially related — diseases closer to each other, which made it easier for researchers to spot possible relationships that might warrant further exploration. This is explained in more detail in Chapter 2.

During this research, the DatAR prototype has evolved from an initial mock-up, Figure 1.2, to a functional multi-widget prototype capable of facilitating simple, Figure 1.3, and more complex literature exploration tasks, Figure 1.4 and 1.5.

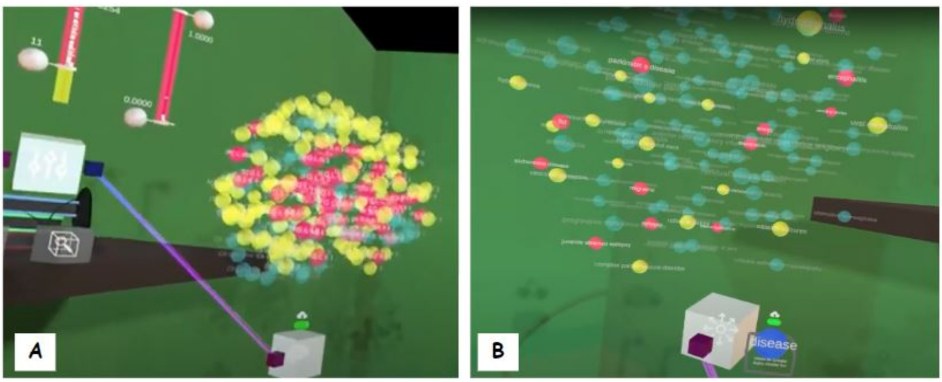

Figure 1.1: DatAR core models. (A) The left-hand side shows a 3D model of the brain with 274 brain regions. (B) The right-hand side shows the brain disease topic model [5].

Figure 1.2: DatAR mockup from 2019. The left-hand side shows a 3D model of the brain with the region Amygdala selected by the user. A slider for selecting a range of the number of co-occurrences is shown to its left. The topics shown to the right of the laptop screen are visualized in the brain disease topic model [6]

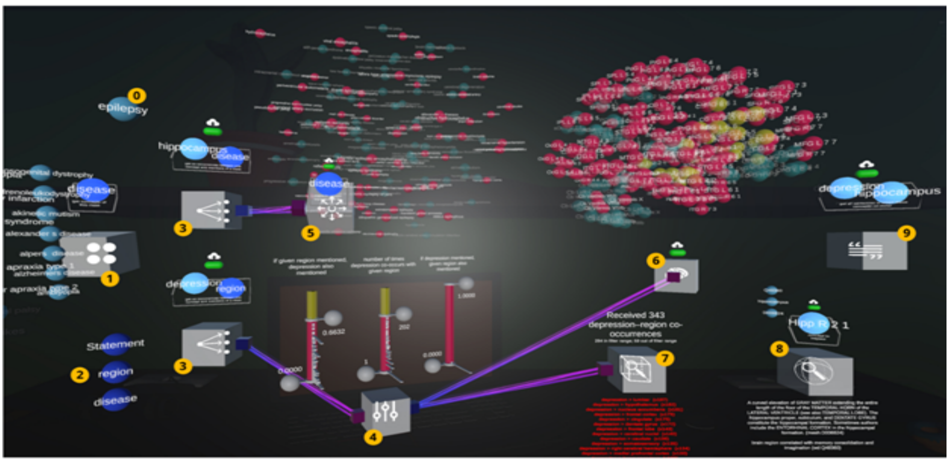

Figure 1.3: Visual summary of DatAR features (2021). Dual Dataflow patterns, initiating from Query nodes (3) and ending at Visualization nodes (5 & 6) [5]

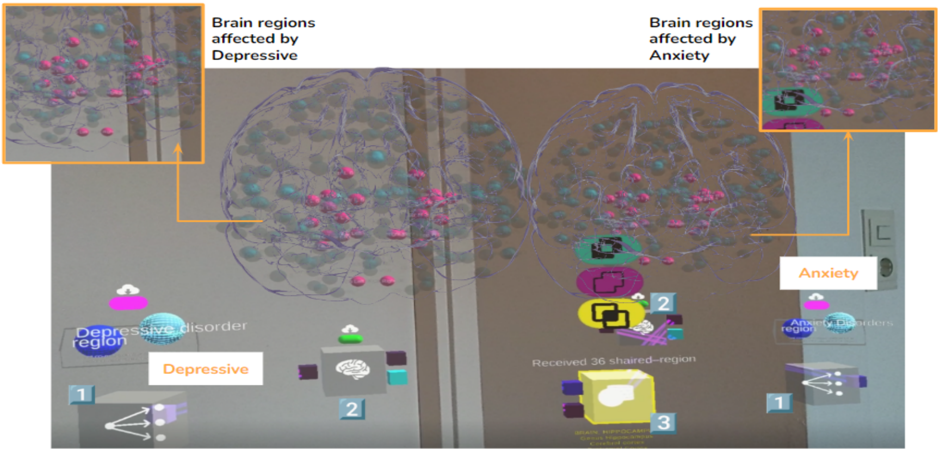

Figure 1.4: The brain visualizations show which brain regions and in which area of the brain (e.g. front, middle, or back) are related to Depressive and Anxiety diseases. "Comparison Widget" helps participants limit the results and make conclusions (2022, Chapter 3).

Figure 1.5: The implemented multiple functionalities for literature exploration (2023, Chapter 4).

1.3. Thesis Structure

The thesis structure is based on three main chapters in which we describe the studies we carried out to answer our ten research questions.

1.3.1. Chapter 2: Designing a Topic-Based Literature Exploration Tool in AR

1

Study 1- Pilot Study: Evaluating the Number of Papers Related to Diseases Associated with the Amygdala

Cunqing Huangfu*[4], a neuroscientist, emphasized to us the importance of examining the relations between brain-related topics before conducting experiments. He suggested that a topic-model-based representation could be useful in visualizing these relationships interactively.

RQ1: How does the DatAR prototype aid in exploring relations between brain topics, and is the tool's functionality useful for topic-based literature exploration?

We considered that diseases with few or no recorded co-occurrences in certain brain regions may signify undiscovered relationships that require additional exploration. Those having a high number of co-occurrences, on the other hand, may also be important since researchers need to verify others' findings. As a result, our approach emphasized these few co-occurrences, assisting users in recognizing previously less studied relationships. The Amygdala, which is associated with 107 diseases, is an appropriate topic for our first investigation because of its reasonable number of relationships.

To address RQ1, we held a prototype demonstration for eight neuroscience BSc students. It enabled the investigation of relationships between the Amygdala and related brain diseases. The goal of the study was to introduce an early version of the prototype, solicit feedback on its usefulness, and understand better which tasks neuroscientists would find useful. We understood from participants that the prototype had the potential to aid in literature discovery, addressing a gap in tools for understanding brain region-disease relationships.

Study 2: Investigating two-direction Relationships between Brain Region and Disease

We developed our user scenario to support relationship-finding by starting from a specific disease. In a new user scenario, when a user selected a disease, they could find related brain regions. To support this scenario, we had to implement the 3D brain model and make the connection with the disease topics. Minimal language analysis was used to find relationships between topics so that it is not known whether a relationship has a negative context such as "no" or "not". To ensure that the relationships between topics were valid, we provided evidence of the relationship by showing the publication and the sentences that contain the relationship. This provided access to the original texts, allowing users to understand the context of relationships.

RQ2: Which neuroscientists' literature exploration tasks are appropriate for support in an AR environment? and **RQ3: to what extent is the functionality we provide in the tool useful for the tasks validated by RQ2?**

Experts in literature exploration evaluated the prototype to address research questions RQ2 and RQ3. Feedback on users' performance, the functionalities' navigation, the explainability of the relationship-finding process, and visualization insights were

[4]* Cunqing Huangfu, Assistant Professor at Brain-inspired Cognitive Intelligence Lab, Institute of Automation, Chinese Academy of Sciences

gathered. According to the qualitative study, the 3D representation of the disease topic model and brain model enhanced participants' understanding of topic relationships.

1.3.2. Chapter 3: Comparing Brain Disease Patterns among Brain Regions

For neuroscientists, it is important to understand how different diseases affect brain regions. Presenting the results for two diseases at the same time is required for a comparative analysis. [7] investigated the similarities in brain regions found in various mental disorders and found that, for example, schizophrenia and depression, are associated with similar brain regions. Similarly, [8] demonstrated the value of researching topics in the literature and linking them with brain regions. The comparison approach assists researchers in gaining new insights into the roles of various brain regions in mental diseases. Within our visualization of comparison functionality, neuroscientists were able to assess which disease was related to which regions and whether both diseases were associated with the same brain regions. Through a topic-based investigation into brain-related topics, we validated comparison functionality in showing disease patterns by affected brain regions.

RQ4: How can we provide usable and explainable *functionality* for comparing relationships between different brain diseases and brain regions?

For this study, we used existing functionality in our previous work to allow neuroscientists to compare two brain region models visually.

RQ5: How is our *visualization* usable and explainable to identify patterns in brain diseases that affect different regions?

We evaluated the usability and explainability of three comparison tasks with participants who had a background in neuroscience or a related field. The provided functionalities allowed users to narrow their exploration and reach conclusions about the potential relationships between brain topics. The qualitative evaluation included "Usability" and "Explainability" to qualify the human-computer interaction feature of comparison functionality.

We developed explainability questions to assess the usefulness of the functionality in assisting neuroscientists in identifying shared brain regions impacted by particular diseases. To assess the effectiveness of provided visualization capabilities, we conducted a study involving participants with expertise in visualization. These participants were tasked with executing the same procedures as those assigned to neuroscientist participants, with a specific focus on evaluating the visualization aspects.

Based on visualization experts' feedback, we improved the visualization of the comparison functionality to answer this question:

RQ 6: How can we develop a visualization that aids in comparing disease patterns among affected brain regions, supporting the multiple relations between more than two different diseases and brain regions?

The same visualization experts participated in evaluating the new visualization to see how much we improved the visualization and how this visualization could support neuroscientists better in comparison tasks.

1.3.3. Chapter 4: Facilitating Neuroscience Topic-based Literature Exploration using Multiple Functionalities in Augmented Reality

Our previous studies were dedicated to evaluating each developed functionality independently, ensuring an understanding of their contributions. This study was designed to investigate the beneficial effect of the multiple functionalities. We investigated how the multiple functionalities could support the discovery of relationships.

RQ7: What literature exploration tasks do neuroscientists use to discover relationships between brain regions and diseases, and how can multiple functionalities support these tasks?

After discussing with three neuroscientists, we identified initial tasks to gain insight into how multiple functionalities could effectively support extensive and realistic neuroscience research scenarios. These scenarios assisted neuroscientists by utilizing the majority of the developed functionalities in a coordinated manner.

We asked two additional questions to better understand our approach's usefulness. First, we considered 'meaningfulness,' asking,

RQ8: To what extent are the multiple functionalities meaningful in supporting the identified compound tasks?

It was important to assess not just the individual functionalities but also their overall effect in practical contexts.

Next, we examined 'explainability' with **RQ9: To what extent are the multiple functionalities explainable in the context of the identified compound tasks?** This question narrows our focus on providing functionality that is clear in displaying detailed results.

Given the importance of visual representation in finding relationships between topics and comparing the results, our next research question focused on evaluating the usability of the multiple functionalities.

RQ10: How do the multiple functionalities of data visualization, navigation, and interaction contribute to finding relationships between brain regions and diseases by improving the user experience in literature exploration tasks?

Visualization experts assisted with the visualization, navigation, and performance aspects, to maximize its use in neuroscience. When it comes to visuals, it was not just about how the functionalities look, it was also about how well it showed relationships between brain-related topics and provided user-friendly navigation.

1.4. Thesis Contributions

This research was motivated by the claim that 3D visualizations presented in AR can assist neuroscientists in finding relations in literature to identify fruitful experiments.

Therefore, this thesis contributes to the field of immersive analytics with a focus on topic-based literature exploration. Our contributions are the following:

- Identification of a number of information exploration tasks that are representative of those carried out by neuroscientists, developed with their collaboration (see Chapter 2, research question 2, Chapter 3, and Chapter 4, research question 7).
- An implementation of relationship-finding functionality as a number of widgets in an immersive AR environment (see Chapter 2, research questions 1 and 3). This includes finding relationships between brain-related topics, aiding in the comprehension of existing relationships, and fostering the discovery of new relationships.
- An implementation of comparison functionality as a widget in an immersive AR environment for comparing the effects of different diseases on brain regions (see Chapter 3, research question 4).
- A visualization to facilitate user interaction with the comparison functionality (see Chapter 3, research questions 5 and 6).
- A confirmation of the meaningfulness and explainability of multiple functionalities for compound relationship-finding tasks as validated by neuroscientists (see Chapter 4, research questions 8 and 9).
- A confirmation of usable multiple functionalities for compound relationship-finding tasks as validated by visualization experts (see Chapter 4, research question 10).

2

Designing a Topic-Based Literature Exploration Tool in AR - An Exploratory Study for Neuroscience

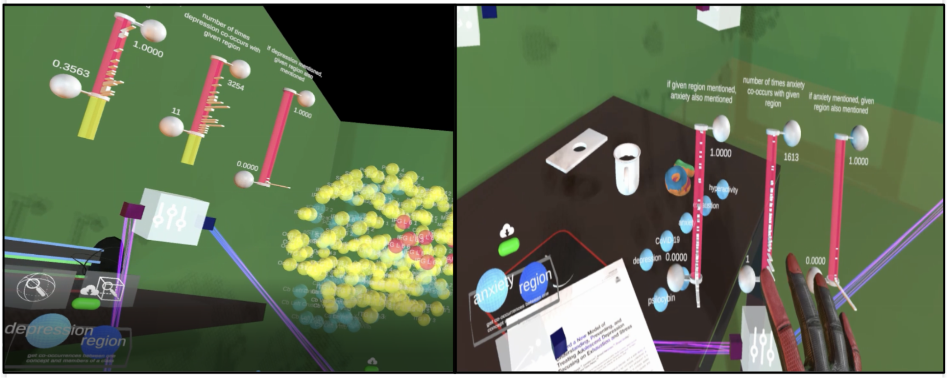

Figure 2.1: Exploring neuroscience literature to find brain regions corresponding to a specific disease. A user investigates brain regions co-occurring with *Depression*, left, and adjusts the filters for co-occurrences of brain regions with *Anxiety*, right.

The large and increasing amount of scientific literature makes it difficult for researchers to analyze and understand relations between topics even in their specific sub-field. Neuroscience researchers are interested in relations between, for example, anatomical regions of the brain and the diseases that affect them. To explore relations in the extensive body of literature, using the topics themselves rather than individual articles, can provide a higher-level approach. We have created a prototype interactive AR environment to learn more about how topic-based literature browsing might aid researchers in analyzing and understanding relations between topics. Given the three-dimensional nature of the brain, we postulate that visualizing neuroscience topics in Augmented Reality would support the exploration of relations between them and thus improve and extend existing literature exploration workflows. We follow a user-centered approach to identify visualization and interaction design requirements. Using an existing analysis of tens of thousands of neuroscience papers, we designed an interactive AR environment to support researchers in finding relations between brain regions and brain diseases that can integrate with existing literature review practices. We carried out two qualitative evaluations to verify our design, first with eight neuroscience students as domain experts and then with seven experienced researchers as literature exploration experts. Our analysis of participants' feedback shows that visualizing topics and their relations in the immersive AR environment is clear, understandable and helpful for topic-based literature exploration, specifically, between brain regions and brain diseases. Our AR literature exploration tool has the potential to be used by neuroscientists in their routine literature reviews.

2.1. Introduction

Literature exploration is a fundamental task in any research endeavor. While searching for individual papers is the traditional approach to exploring literature, one of its key drawbacks is the difficulty to explore complex relations among topics[1]. We postulate that much effort can be saved, however, by allowing researchers to explore literature via topics. This would enable researchers to analyze relations between topics across papers: e.g., which pairs of topics co-occur frequently in papers [9]? Our goal is to investigate to what extent topic-based, rather than article-based, exploration allows researchers to more efficiently select and find relations among topics from large amounts of literature [10, 11]. To investigate this, we construct a prototype interactive AR environment containing an analysis of literature from the neuroscience domain[2]. One of a neuroscientist's research goals is to identify high-potential relations that could form the basis for a future experiment. Assessing which experiment should be run next requires an understanding of which relations are regarded as established in the literature and which are novel or unproven[1].

In our neuroscience use-case, our aim is to support researchers by providing a 3D exploration environment to find and visualize relations between topics in an easy and understandable way. This allows us to visualize relations directly with sub-regions of a 3D virtual brain and to explore structures in 3D. The use of spatial layouts of information in virtual and augmented reality has been proven to assist recollection and simple visual exploration [12]. However, there have been few attempts to investigate how spatial cognition aided by immersive technologies could help literature exploration [13]. Our overall research questions are: **RQ1: Which neuroscientists' literature exploration tasks are appropriate for support in an IA AR environment?** and **RQ2: to what extent is the functionality we provide in the tool useful for the tasks validated by RQ1?** We follow a user-centered design approach by involving neuroscience and literature exploration experts at the early stages in the design. We validated the main task which we support in our prototype by neuroscientists participated in the first study. Considering these experts' opinions, we improved our preliminary user scenario and asked literature exploration experts to evaluate comprehensibility of the analysis process, prototype environment and cognitive task limitation in the second study. Because of the COVID-19 outbreak we were unable to invite evaluation participants to use our AR environment so simulated it in VR ("Evaluation" section, 2.6) for the second study. We contribute design requirements and recommendations for the development of immersive analytics tools to support neuroscientists in performing topic-based literature exploration.

2.2. Related Work

To create an immersive environment to explore neuroscience literature, we need to understand how topics are extracted from the literature and incorporated into a "topic model", 2.2.1, and how finding relations between neuroscience topics can be visualized to reduce the need for technical experience and increase the understanding of relations, 2.2.2. Given that our proposed display environment is augmented reality, we discuss visualization work related to neuroscience, 2.2.3.

[1]Personal communication with Cunqing Huangfu, a neuroscientist.

[2]We use the Linked Brain Data (LBD) repository as an example of a topic-based analysis of neuroscience literature: http://www.linked-brain-data.org/index.jsp?link=link

2.2.1. Exploring Biomedical Literature

Neuroscientists are interested in understanding relations between brain-related topics to find fruitful areas for experimental studies. Literature exploration supports the discovery of hidden and unknown relations by (semi-)automated analysis using machine-learning techniques. Exploring literature can be used by all of the scientific areas not only biomedical domains [14–16]. Biomedical work using this method varies from identifying new connections between genes and illnesses, relations between different diseases, predicting drug reactions and discovering new research areas [17, 18]. To find out relations between brain-related topics and grouping similar topics in our work, Latent Dirichlet Allocation (LDA) method [19] is applied on the abstract and title of neuroscience literature and presents semantically similar brain diseases.

2.2.2. Linked Data Visualization

The Linked Brain Data (LBD) publication repository we use is an RDF[3] repository of extracted, linked and organized neuroscience publications. The repository has access to the title and abstract of publications from online neuroscience resources such as PubMed. Visualizing Linked Data (LD) can help users without technical skills to understand the meaning of content [20]. Several tools offer interactive operations for presenting LD graphs generated from data files or SPARQL endpoints. They present topics as graph nodes and support zooming into/out of the graph along with filtering and editing nodes and edges [21–24]. For example, Tarsier [25] presents LD sources as interactive 3D graph visualizations. The authors highlight the role of a 3D visualization to understand and analyze this type of data. Providing an intuitive visualization of extracted topics from LBD is crucial to reducing the need for technical skills for neuroscientists.

2.2.3. Immersive Visualizations of Brain-related Topics

Immersive visualizations have already been used to support neuroscientists in tasks other than literature exploration. For instance, in presenting the brain connectome, Connectome Visualization Utility, Brain Net Viewer and Connectome Viewer Toolkit use 3D node-link diagrams to support neuroscientists in observing relations between connected nodes [26–28]. For complex abstract 3D structures that need to be analyzed, 3D-stereoscopic visualization improves the spatial understanding of cells [29]. Also, it is easier to establish relations between brain structures, functions and connectivity in IA [30]. The NeuroCave application uses immersive analytics to support neuroscientists in exploring complex characteristics in network-theoretic approaches [31]. Using a VR headset helps brain researchers to interact with connectome and cluster brain regions into different groups. It shows that users appreciate using VR environments for presenting 3D data – brain regions – more than a desktop environment. EPES connects MRI and iEEG data by labeling, coloring and animation in a VR environment. The authors show that employing VR for presurgical epilepsy evaluation can help integrate iEEG and MRI data and visualize seizure propagation [32]. Our tool is different from previous work by supporting users in exploring brain-related topics from the literature

[3] Resource Description Framework, World Wide Web Consortium specification, https://en.wikipedia.org/wiki/Resource_Description_Framework.

and their interrelations and presenting them in an immersive environment.

2.3. Design Requirements

A neuroscience researcher[1] provided our initial user scenario (relation-finding) and helped us determine a real neuroscientist's task: to find diseases related to a brain region (e.g., Amygdala[4]). Our design requirements are based on functional requirements that came from neuroscientists' and data discovery experts' opinions and were identified during the tool implementation.

2.3.1. DR1: Co-occurrences

Present a wide range of co-occurrences of brain diseases with a brain region. The number of co-occurrences of a topic pair indicates the number of times that a topic, such as a specific brain disease, appears in the same sentence as another topic, such as a brain region. Based on a neuroscientist[1] opinion, diseases that co-occur with a brain region in the literature a few times, or even zero times, can be useful, since they may indicate new research areas for investigation. However, diseases with a high number of co-occurrences are also important, because they verify other researchers' findings. A neuroscientist should be able to explore a wide range of co-occurrences to form an understanding of the relations among the topics in the literature.

2.3.2. DR2: Neighboring Diseases

Identify unexplored brain diseases that may affect a brain region. This requirement came from a neuroscientist[1] who hypothesized that brain diseases that are semantically similar may affect similar brain regions [7, 8]. Brain diseases that are unrelated to a brain region but they are close to the related one are "Neighboring diseases" and can be promising areas for investigation. Our colleagues in Brain-inspired Intelligence group applied the LDA topic model method and t-distributed Stochastic Neighbor Embedding (t-SNE) algorithm in the abstract and title of neuroscientific publication, yielding 3D locations for around 300 diseases[5]. The distance between diseases gives an indication of their semantic similarity. Figure 2.2 shows a 3D Topic model visualization of diseases. We have to provide an environment to support neuroscientists in identifying neighboring diseases.

2.3.3. DR3: Select Topic

Select one or more topics in the topic model and brain visualization. Users need to be able to select a single topic, such as brain region or brain disease for further investigation, and to select (at least) two diseases in the topic model, to allow a comparison of co-occurrences of each disease with brain regions (e.g. see [33]).

[4] We select the Amygdala as an example since it has relations with about 107 diseases, which is neither very many nor very few.

[5] To preserve the structure of low-dimensional data such as high-dimensional, we prefer 3D dimensions rather than 2D.

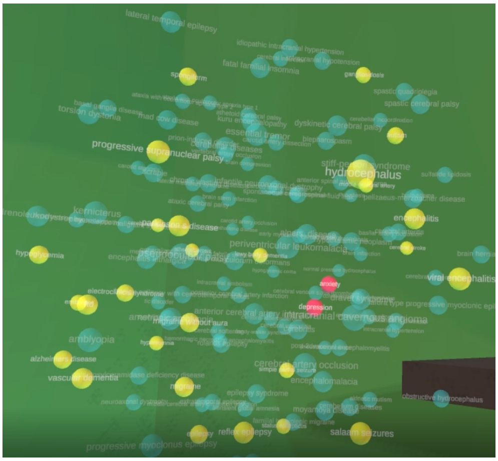

Figure 2.2: 3D topic model visualization of around 300 diseases. Depression and Anxiety are located close to each other in the LBD topic model which may suggest that they might affect similar regions.

2.3.4. DR4: Identify Related Topics

Users need to be able to identify the 1-n relations between topics. Users need to be able to select a brain region/disease and request all related diseases/regions.

2.3.5. DR5: Identify Sources

Provide access to the source literature. This requirement was derived from a brainstorming session with three data discovery experts and three AR/VR developers. During the process of creating the LBD repository, there was relatively little language analysis on the relation between two topics found in a single sentence. A single instance of a co-occurrence is counted when two topics are present in the same sentence and there are no negative words such as "no" or "not" in the sentence. There is no other validation of the meaning of the sentence. For example, "The relation between region A and disease B has been questioned." or "The relation between region A and disease B has been falsified." are both sentences in the dataset that provide evidence of a relation between region A and disease B.

This leads to the requirement that users should be able to access the sentences in the original document, represented by the co-occurrences corresponding to a query, to allow them to assess the positive or negative contribution to the relation.

2.4. Design Rationale

We discuss the trade-offs made during the design process to satisfy one or more of the design requirements and provide our reasoning for making specific design decisions.

2.4.1. Visualizing Numbers of Co-occurrences

A visualization of the numbers of co-occurrences between a topic pair needs to be able to deal with both high and low numbers of co-occurrences (DR1, 2.3.1). One option would be to indicate the number of co-occurrences by different sphere sizes, where each sphere is a disease/region. For example, as proportional to the number of co-occurrences, to indicate established knowledge, or inversely proportional, to indicate the importance of unexplored research areas. Gauging sizes visually is difficult, however, especially for topics with similar numbers of co-occurrences. Also, differing sphere sizes can lead the user to misinterpreting the distance between two spheres that is used to indicate similarity in the topic model and relative positioning of brain regions. We instead use the same size and shape for different numbers of co-occurrences and include a filter that allows users to select the desired range. Rather than being confronted with a tool that hides (potentially) unrelated results, users should be supported in highlighting parts of the result to retain context. For this, we select different colors of same-sized spheres to indicate each result category:

- Topics within the filter range (red sphere)
- Topics related to the query but outside the filter range (yellow sphere)
- Topics unrelated to the query (turquoise sphere)

2.4.2. Visualizing Neighboring Diseases

To detect neighboring diseases (DR2, 2.3.2) based on their positions in the topic model, we consider two alternatives. The first is to use clustering methods to find close diseases. Each clustering method, however, has its own shortcomings, and to avoid misleading results, they need to be validated by a domain expert [34]. An alternative is to present diseases based on their 3D positions in the topic model and allow users to visually identify groups of diseases. This position-based exploration depends on users correctly interpreting the relative positions of brain diseases. To visualize the topic model, we can present this on a 2D screen, or in an immersive environment. Given the high cost of a neuroscience experiment, it is vital that the visualization supports users as much as possible in finding neighboring diseases, so a clear representation of the distances among them is crucial. We propose a 3D immersive environment since users should be able to see more information from an unlimited virtual 3D display than from a limited 2D display [35].

2.4.3. Interacting with Topics

The two requirements, Select Topic (DR3, 2.3.3) and Identify Related Topics (DR4, 2.3.4) determine how the user should be able to interact in the environment. We consider a simple grabbing action for selecting topics since it is a natural and common action for users, particularly in immersive environments. We provide a duplication feature for all of our widgets, analysis tools in the immersive environment, and topic spheres to support users in parallel investigations of multiple queries and result comparison. To satisfy DR4, the exploration tool supports different relation-finding queries so that users do not need to know technical query languages when they want to find relations.

2.4.4. Identify Sources

Our tool identifies correlations between topics and does not imply that there is a causal relation – it is the neuroscientist who creates an understanding by exploring the source literature. The co-occurrence analysis of the source literature is made available in the LBD repository. To provide access to the publications corresponding to the result of a query, we need to create a connection between our environment and PubMed (DR5, 2.3.5). The user is then able to see the source papers and the sentences that contributed to the co-occurrence analysis. This part of the exploration environment shows sentences and papers based on the selected topics, Figure 2.3. Our goal is to allow the user to determine the reason for the relation provided in LBD, so the sentences displayed correspond only to one disease and one region.

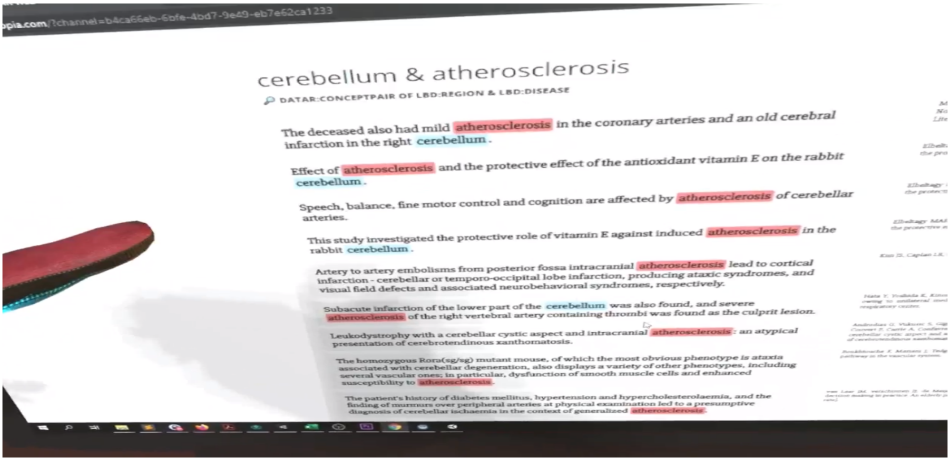

Figure 2.3: Sentences from and links to the papers that mention both "Atherosclerosis" and "Cerebellum" in their titles or abstracts are shown in a web browser.

2.5. Implementation

2.5.1. First Prototype (AR)

Visualization

We designed and implemented a number of widgets for different purposes. Widgets are analysis tools that perform actions such as querying, data manipulation, visualization or data export [5]. Most of the widgets need user input that should be placed in the widget's receptacles. Receptacles are for placing category or topic inputs. **Category** refers to a head of a class and **topic** refers to the component of that class (e.g., Disease is a category/class and Depression is one of the topics of that category). The tool generates the visualization of widgets when the user grabs them.

Our main visualization is the **Topic Model of brain diseases** (W_{TM}) from the Linked Brain Data repository (Subsection 2.3.2 and Figure 2.2). We use a **Class Retriever widget (W_{CR})** to show a list of brain regions instead of brain visualization. Other widgets are:

Co-occurrence Querier Widget (W_{CQ}): The widget is designed to connect to two 3D models and shows which regions/diseases are related to the selected topic.

Min-Max Filter Widget (W_{MMF}): This filter limits the results based on three factors; P(Topic A|Topic B), P(Topic B|Topic A) and the number of occurrences topic A and topic B. The first factor is the probability of topic A occurring in a sentence, given that topic B occurs in that sentence. The number of occurrences indicates how many times these two topics appear in the same sentence.

Technical features

The AR visualization was built with Unity3D (v2019.3.9f1). In the AR version we use MetaSDK(v2.7.0.38) to work with the Meta 2 HMD.

2.5.2. Second Prototype (VR)

Visualization

We used all of the visualizations of our first prototype and added some more widgets to develop the tool.

Sentences Extractor Widget (W_{SE}): The widget gets two topics and connects to the system's web-based companion application and shows all of the sentences and links to the papers that indicate both those topics.

Resource Sphere Inspector Widget (W_{RSI}): The widget provides the description of a brain region and provides extra information from Wikidata, MeSH and Scalable Brain Atlas (SBA)[6] project.

Dataflow Inspector Widget (W_{DI}): This widget shows the result of the Co-occurrence Querier Widget by text.

All of the widgets and icons are presented in Figure 2.4.

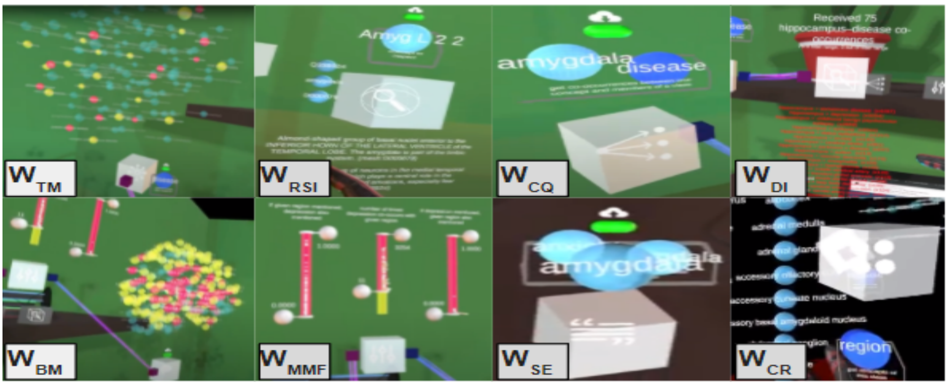

Figure 2.4: Visualization of the widgets.

[6]https://scalablebrainatlas.incf.org/services/regioncenters.php

The **3D Brain Model Widget (W_{BM})** is based on 3D region positions provided by the SBA. The tool highlights regions in the 3D brain based on a user's query. Most regions have multiple names based on different conventions known by a neuroscientist. To ensure that these are correctly highlighted in the tool, we created a mapping from the different names to the name displayed. Two neuroscientists helped us in mappings for the 561 regions.

Technical features

The technical setting of the tool is based on simulating an AR environment consisting of VR HMD that is built on SteamVR (v2.5; SDK v1.8.19). The web-based companion application was developed in Angular (v8.2.14).

2.6. Evaluation

We ran two studies with the goal of allowing participants to explore the functionalities of the tool. The tool was further developed after the first study. Since the main task (relation-finding) was the same in both studies, we consider that the precise changes made are irrelevant and thus do not describe them here.

The COVID-19 outbreak meant that we were unable to invite participants into the lab for our second study. We adapted the implementation to VR that simulated an AR environment, Figure 2.5, allowing us to find participants who would be able to evaluate the prototype using their own equipment. Because we were unable to find neuroscientists with at-home access to a VR/AR device, we invited participants with literature exploration experience to our study. We measure our evaluation goals through interviews. Answering the questions did not require a neuroscience background because: (1) the literature exploration aspect of the tool is relevant to all researchers, (2) we provided an explanation of the neuroscience literature case study used in the prototype to participants before carrying out the task, (3) our goal was to evaluate doing work right, not doing the right work.

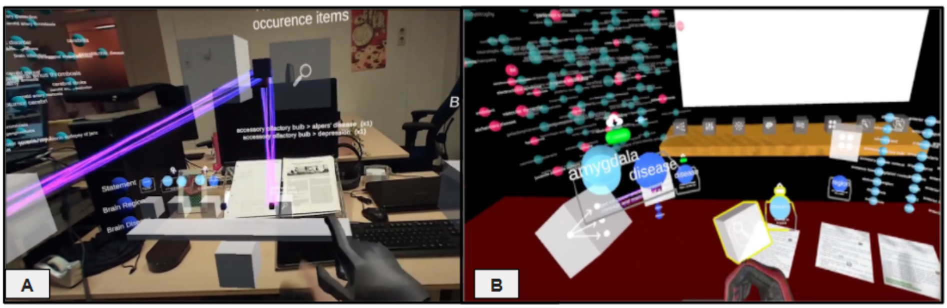

Figure 2.5: The prototype tool in AR (A). Participants can use virtual widgets to carry out the relation-finding task. Simulated tool based on the usual researcher workplace in VR (B).

Based on the user-centered design approach, we were eager to collect opinions that enable us full and rich descriptions rather than to make statistical inferences. So, we applied qualitative content analysis to analyze the transcribed data (interviews for both studies). These types of studies offer the potential for improved understanding of existing practices (meaningfulness and explainability), analysis environments (visualization and navigation), and cognitive task limitations (performance) as they happen during running the tasks [36]. To answer our research questions and evaluate all important features in our design, we grouped our evaluation goals into five categories; meaningfulness, explainability, visualization, navigation, and performance. The interview questions of both studies were designed based on the guiding scenario for information visualization evaluation [37]. The concepts of data, tasks, and visualization can be combined in two ways to ask different questions [38]:

- Data + Task = Visualization? – Find an appropriate visualization for a given task and data.
- Data + Visualization = Task? – Consider as an evaluation process and answer the question of how well can tasks be performed on this data using this visualization.

For these studies, we investigated the first combination.

We asked participants to record their screens during the session. Then, we watched their recording and measured their performance (observation evaluation for the second study). The observation evaluation was analyzed in terms of the (1) time needed to perform the tasks, (2) number of errors a participant makes, (3) quantity of the information obtained, and (4) accuracy of task completion [39].

Literature Topics: The topics derived from the literature analysis were gathered from neuroscience publications from online resources such as PubMed and are stored as the LBD knowledge graph. LBD contains a set of topics identified and classified within the publication's title and sentences of the abstract. Brain diseases, brain regions, cognitive functions, and neurons are some of the topics in the LBD. For these studies, we investigate how participants are able to explore relations between brain regions and diseases.

2.6.1. Evaluation with Neuroscientists (AR)

Evaluation goals

In this study, we tried to find the answer for our first research question (RQ1).

- To assess to what extent participants understand the concept behind the tool [**Meaningfulness**].
- To obtain suggestions from participants for custom modifications or additions and novel uses for the tool [**Meaningfulness**].
- To obtain suggestions from participants for improvement in next iterations [**Meaningfulness**].

Participants

Eight senior bachelor students in the field of neuroscience participated (P1-P8). They had an understanding of neuroscience literature and were able to evaluate the prototype with respect to their own neuroscience research goals. The session was in-person

Table 2.1: Example tasks for January 2020 study

Task	Description
Relation between the Amygdala and Brain Diseases	The participant was asked to describe their understanding of the Topic Model and if this was incorrect, the researcher explained it again. The participant was then asked to use the Topic Model to find the diseases related to the Amygdala.
Relation between a region and Brain Diseases	The researcher reset the environment. The participant was asked to investigate again without any guidance. They had to select their desired brain region and do the same steps to find related diseases.

and they used a Meta 2 headset.

Procedure and tasks

Each session started with an explanation about the Linked Brain Data analysis of neuroscience literature and the relation-finding barriers for the neuroscientists continued by an introduction to the tool (15 min). Participants then performed the tasks (20 min) and were interviewed (30 min). The test sessions lasted about an hour.

Participants were asked to explore the relation between the Amygdala and associated brain diseases. After this session, we improved our preliminary user scenario based on the information that we gathered from these neuroscientists. For example, we added the ability for participants can run a reverse scenario, asking for related brain regions when a disease is selected. Table 2.1 shows tasks and a short description.

2.6.2. Evaluation with literature exploration experts (VR)

Evaluation goals

Our goal was to answer the second research question (RQ2) by examining the following items.

- To identify the salient points of our tool that participants found (positive and negative) [**Explainability**].
- To identify whether the participant can explain the analysis process of the tool (comprehensibility of the analysis process) [**Explainability**].
- To find which barriers prevent participants from following task steps [**Performance**].
- To find the influence of representing information in space [**Navigation**]. Since some parts of data that will be presented is 3D, evaluate whether an immersive space can improve presenting the data from different perspectives.
- To evaluate the readability of the 3D visualization [**Visualization**].

Participants

Seven participants with experience of reviewing literature, but not neuroscience literature (P9-P15), took part using their own steam-VR compatible headset. They had an

Table 2.2: Example tasks for June 2020 study

Task	Description
Relation between Amygdala and Brain Diseases	The participant was asked to use the Topic Model to find the diseases related to the Amygdala. The participant was then asked to use the filter to find related diseases with more than 400 number of occurrences.
Relation between a related disease and Amygdala	The participant was asked to look at sentences that indicate the relation between one of the related diseases from the previous task and Amygdala. They had to read the sentences and check the negative ones on the browser.
Relation between a disease and Brain Regions	The participant was asked to grab an unrelated disease that was semantically close to the related one in the Topic model and find related brain regions in the 3D brain visualization.
Finding additional information about the regions	The participant was asked to select at least one related brain region from the previous task and generate descriptions and closed topics by Resource Sphere Inspector Widget.

understanding of the literature exploration task and were able to reflect on their experience, their understanding of the prototype's functionality, and their observations on the visualization.

Procedure and tasks

Each session started by asking participants to read a document introducing the study (8 min). We provided them with seven short videos of the tool environment and a sample of user scenarios (13 min). They ran the tool and carried out four tasks (30 min) and then interviewed (20 min). The whole session took approximately one hour.

In this session, participants were asked to consider themselves as a neuroscience researcher and initiate new research about Amygdala and related diseases by doing four tasks. Table 2.2 shows tasks and a short description.

2.7. Results

We investigated all five evaluation categories (Section 2.6) in both studies. Since meaningfulness is relevant only for participants with neuroscience knowledge, we analysed the results for this category only for the January 2020 study. The results of the other four categories provided by literature exploration experts are valid since useful, critical, feedback relies on a smooth interaction experience, which was better in the VR version than the AR version. A VR version could better reflect what the AR version could be in the future (given sufficient development, as it is a less-developed technology).

2.7.1. Neuroscientists with initial AR prototype

Meaningfulness

To satisfy our mentioned evaluation goals on meaningfulness and back to our first research question (Section 2.1), we tried to understand the neuroscientists' methods for finding relation between topics and make sure that they understand the idea behind the prototype.

More than half of the neuroscience participants perceived the prototyped tool as valuable for exploring literature based on topics. Participants expressed that they did not have appropriate tools to find relations between brain regions and diseases, "*it is a whole gap in science*" (P8). All participants mentioned that if they want to explore the relations between two topics, they go to PubMed or other online resources and search the keywords. As they stated, it is hard and time-consuming work: they have to read at least the abstract of each paper to explore whether the two selected topics are related. Furthermore, if they could not find any direct evidence, they have to check indirect relations by considering a third topic, "*...Go to the PubMed website and type a concept, go to the literature, and try to find a relation. For new relations try to use internal connections between two concepts (e.g., use the cognitive function concept as a middle concept). Or search for a semantically similar concept that already has the relation.*" (P4).

The task of finding little-explored relations in academic literature was meaningful to all participants. Our approach to complete the relation-finding task was deemed worthwhile by seven participants (P1-P4, P6-P8), "*...So it does really narrow it down before you have to do all the thinking*" (P3); but P5 had to conclude that "*...for some people can be helpful but for me, no*". Five participants (P1-P3,P6-P7) said that the environment was visual and informative and had the potential to be an option for literature exploration, especially before an in-depth review.

In terms of functionality, we received some suggestions to improve the tool. The ability to search, delete and read the objects[7] or returning to the previous step was mentioned by P5. Also, they found the idea of accessing the source sentences and papers interesting (P1,P5,P6), "*It's just a supportive tool; you need to check yourself, be critical of what is shown*" (P7).

2.7.2. Literature exploration experts with VR prototype - Interview

Explainability

The prototype encouraged participants to have a purpose for the task and try to think like a neuroscientist. "*Although I am not a neuroscientist, I want to make sense of the task.*", P9. "*Especially for someone who works in those brain-related fields, it would probably be beneficial to see some areas light up while you play with some filters and say these might be related*" (P12).

Almost all of our participants agreed that we chose an effective and intuitive way for visualizing data operations. In particular, The 3D representations of the topic model and 3D brain were found to be intuitive. P9, who has data analysis experience, indicated the depth of analysis as a clear part of the analysis process in the tool. For example, the ability of the prototype to present source sentences and papers when browsing the

[7] Object refers to any virtual object in our tool like widget and resource spheres.

relation of two topics was helpful. "*It's a good workflow to teach us. OK. This concepts*[8] *seem related. Now let's see what the literature says. So I think that's a good way to support your theory, support your hunch or your suspicion that the two concepts are related*" (P11). To improve this part, participants suggested adding the ability to check why two diseases are close to each other in the topic model (P15).

Performance

Participants stated that they wished to have more help during running tasks. They perceived this as a barrier to the task completion. They had difficulties with the similarity of the widget icons (resource sphere inspector widget and dataflow inspector widget) which impeded selecting the correct widget. Grabbing small objects with large virtual hands was another impediment that participants mentioned. In terms of functionality to improve performance, some participants (P11, P14) suggested a manual that can help participants when they need to know widgets' functionalities, "*...So proper labeling, proper widget tipping and a search function, that would be helpful.*" (P11). Storing the participants' findings is another function that boosts participants' performance. For example, a spreadsheet that shows the participants' actions and results is displayed (P13) and "*...do a voice recording or something and then put that somewhere for later ...*" (P14).

Navigation

The domain experts perceived the immersive technology as valuable. They reported that the 360° environment facilitated more space for literature exploration. Having floating topic spheres in the immersive environment and navigating among them was found to be convenient, "*Well, it's very convenient to just put stuff floating in space. So there's plenty of room to do it.*" (P11), "*I like our power. I liked the fact that I could put everything everywhere so that, you know, I had a 3D workspace that was very handy.*" (P14).

Although some visualizations, such as presenting the result text of one of the widget in red, misled participants about the correctness of their actions, others were perceived as very helpful. The green icon when the widget receives the results of a query and the purple rope when two widgets were connected in the right way supported participants in taking the correct actions, "*I like the visual feedback where things are connected: the icon turns to green, so you know that it's working*" (P9). The results showed that working with the tool was not difficult, but for the first time, participants needed instruction. Almost all participants indicated that the 3D VR prototype is more enjoyable than working with a 2D screen. As one participant said, however, "*it really depends on the use case and for a neuroscientist that should find relations between concepts among a lot of literature using such a tool makes a lot of sense*" (P9).

To improve the interaction functionality, participants suggested having the ability to collaborate with their peers during working with the tool (P9).

[8]For the study of participants, we used the term "Concept" instead of "Topic".

Visualization

Participants found the topic model and brain region visualizations useful (P10, P11, P12). Visualizing the topic model in an immersive environment allowed participants to distinguish neighboring diseases by only moving their heads in/out the model, "... *just moving around concepts, you know, like Tom Cruise in one movie*". They (P13) agreed the immersion helped them concentrate on the subject matter. On the other hand, based on many comments (P9,P11,P12,P15), the names of spheres in these two 3D plots overlap with each other, so the readability of names was challenging. The favorite features participants mentioned were the **3D visualizations of the topic model and brain region** (P10-12), **exploring sentences** and the **360° data analysis environment**. Participants were able to run all sorts of queries quickly. They also liked the color filter that could help them to highlight the results by changing the topic spheres' color, rather than removing them from the display. Some of the visualization improvements suggested by P9-P12:

- Using different colors for the diseases and region spheres. This can help them to recognize disease and region spheres when they have been moved in the environment after several grabbing actions.

- Considering another visualization for the list of regions' names.

- Adding a search function that can find a typed region name can be beneficial.

- Informing participants whether they chose their desired spheres.

2.7.3. Literature exploration experts with VR prototype - Observations from screen recordings

Time needed to perform tasks

The time that it takes to complete the tasks are different between participants. For example, the maximum time for completing task 1 was 15:33 minutes and the minimum was 02:14 minutes, figure 2.6. For some of our participants, it was the first time that they worked with VR devices. As the screen recordings show, the reason is sometimes that the headset and controllers technology did not work properly and sometimes that the participant has little experience in using the VR device.

Number of errors a participant makes

All participants made at least one mistake in running tasks. Some of the mistakes derive from participants' not reading instructions carefully and other ones relate to design flaws, such as misleading visualizations for some parts of the tool. For example, the W_{RSI} and W_{DI} (Figure 2.4) have similar icons and participants with vision problems had difficulties selecting the right one.

Quantity of the information obtained

We evaluate how experience that participants obtain from working with the tool helps them to run the next tasks quickly. By observing the process of performing tasks we conclude that while there were more steps in the first task, participants were able to complete the next tasks faster. The process of learning to work with the tool is prom-

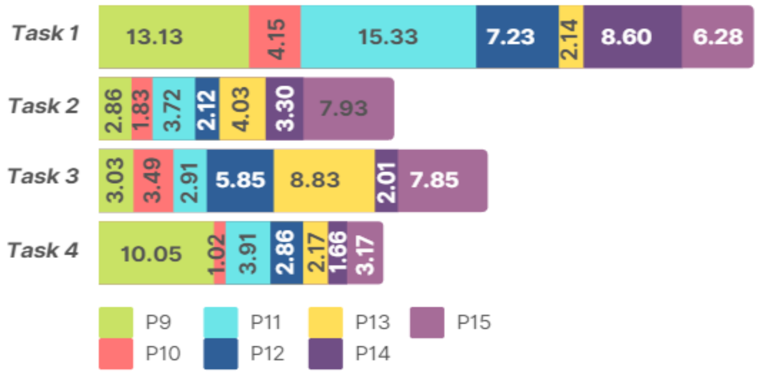

Figure 2.6: Time needed to perform each task by participants.

ising, but we should improve the tool environment in terms of navigation.

Accuracy of task completion

After watching the screen recordings, we understand that two participants ran one of the steps in a task wrongly. In that step, we asked participants to select a disease with some features but they ignored one of them. Since their mistake did not disrupt the overall process of working with the tool, they did not realize their mistakes. This problem is more related to the open-ended overall purpose of the tool (finding unexplored relations) rather than to the deficiency of the tool design. At some point in the study, all diseases in the topic model related to the Amygdala are shown in red. We asked participants to select another disease that is semantically similar to the selected disease (shown in red) that is not already related to the Amygdala. If participants understand the topic model, they should know that diseases unrelated to the Amygdala (turquoise) close to the selected disease (shown in red) are correct. If participants are not aware of this distinction and only choose a random disease, they can not find any evidence of possible relation between the selected disease and region.

2.8. Discussion

Exploration Environment: Neuroscientist participants stated that they would be prepared to use the tool in their daily practice if the interactions improve significantly[9]. Considering the capabilities that immersive analytics (IA) provides for participants, such as the intuitive presentation of 3D graphs and a 360° workspace, we do not intend to move to the limited 2D/2.5D environment on screen. While an IA environment is uncommon for exploring literature, exploring existing relations and finding new ones is intuitive and understandable for participants. Three of our neuroscientist participants expressed the wish to include relation finding in their own 2D workplace; indicating that the environment needs improvement but the rationale behind the ap-

[9] We have recently purchased a Hololens 2 headset and the interactions are much more natural and with less effort in grabbing and selecting virtual objects.

proach shows promise.

Topic Sphere Visualization: To indicate to participants which topics have been filtered out from the query on the basis of co-occurrences, we used red to indicate topics still within the filtered query and yellow for those outside the filter boundaries. Using bright (e.g., yellow) and warm (e.g., red) colors in the same visualization can lead to incorrect visual assessment of the depth perception and hence the distance between topics. To improve the visualization, we have to rethink the color of the topic spheres if we want participants to perceive their correct position.

In addition, long topic names are challenging to read and currently overlap with the longer topic names (majority of names). We need to adapt the topic sphere layout algorithm to take the length of the topic name into account. A zoom feature would also be useful.

Selecting Brain Region: For now, there is no direct connection between brain visualization and topic model. When a participant wants to find the relation between a brain region and brain diseases, they need to use the "Co-Occurrence Querier" widget. We intend to improve the implementation so that participants can select a region in the 3D brain and see highlighted diseases in the topic model.

2.9. Conclusions and Future Work

We designed an augmented reality tool that presents an interactive overview of the relations between brain diseases and brain regions. The goal of our design is to support neuroscientists to explore literature to identify the most suitable experiments to carry out. Through the use of our prototype tool, expert neuroscientists should be able to form an understanding through exploration of the tool's representations of topics in the literature. To answer our second research question (Section 2.1) and based on feedback from neuroscientists on the initial AR prototype, the tool has the potential for use as part of a serious research endeavor.

Our tool design could be extended to explore relations between other brain-related topics such as genes, neurons and proteins. Our work can be generalized to other research domains, but some of the visualizations, such as the disease topic model or visualization of the brain, should be redesigned based on the related topics.

In the topic model, while the requirements could be extended to allow users to select three or more diseases, the relations between any two diseases are based on the analysis of two topics occurring in a single sentence. Our approach is to consider only the simpler case to discuss with neuroscientists for this design and potentially consider this for future work.

One of the positive features of the IA environment, in particular AR, is to support collaboration. Collaboration fosters discussions and helps to explain findings. In this case, it is essential to provide a shared exploring environment by similar points of view and a private one with different points of view for each of the participants.

We are at the beginning of a process. We have shown that AR provides a suitable environment for topic-based literature exploration and intend to continue to develop the design of the environment.

3

Comparing Brain Disease Patterns among Brain Regions by Analysis of Neuroscience Literature in Augmented Reality

The video of this chapter is available here: `https://youtu.be/iC6JZ860iks`

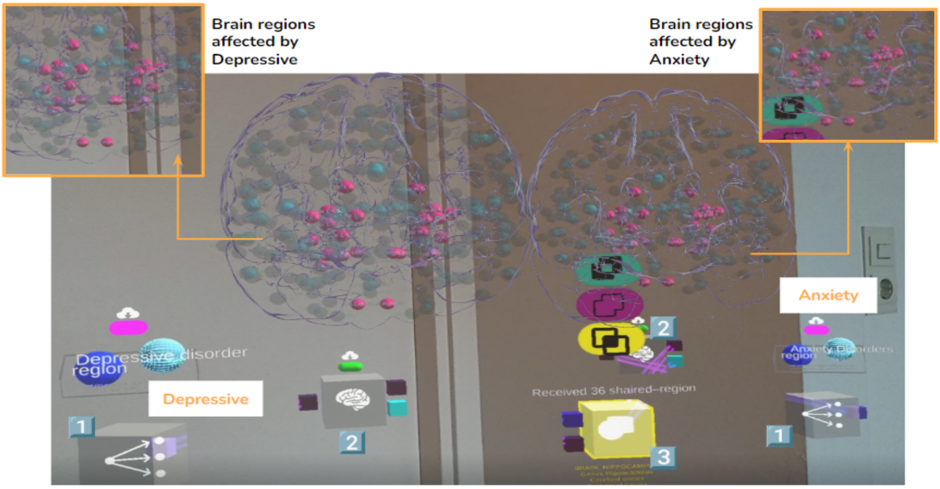

Figure 3.1: Querying (cube 1) for affected regions by *Depressive* and *Anxiety* using Comparison Functionality (cube 3). Brain visualizations (cube 2) highlight the affected regions as pink spheres.

Neuroscientists are interested in finding relationships between brain topics by comparing disease patterns in affected brain regions. Current studies tried to consult many papers in the literature, allowing neuroscientists to compare these relationships slowly. To enable more efficient exploration and comparison of which brain regions are affected by which diseases, we use visualizing relationships in Augmented Reality (AR). Using a user-centered design approach, we (i) confirm the usefulness of the disease comparison task, (ii) identify representative tasks for our study, and (iii) design, implement, and evaluate suitable functionality in an immersive AR environment. Six neuroscientists and nine visualization experts took part in an initial study to evaluate the usability and explainability of the visualization. Based on their feedback, we made two key improvements: enhanced our visualization techniques and upgraded the tool's functionality to support multi-comparisons. The findings from feedback show that using an immersive AR environment offers an intuitive visualization of brain regions affected by specific diseases. This approach also promotes a deeper understanding for neuroscientists after using the functionality: they can explore and analyze complex relationships and patterns by selecting a small number of related papers to read to gain a more in-depth understanding without the need to review an extensive number of publications.

3.1. Introduction

Neuroscientists search the literature for similarities and differences in which brain regions are affected by which diseases [7, 8]. Traditional methods frequently utilize 2D representations to map brain diseases onto reported brain activation data [8]. We explore functionality development to provide a utilized understanding of disease patterns in multiple brain regions. Given the three-dimensional nature of the brain's structure, 3D representations can improve the visualization of brain anatomy and identification of affected regions, allowing for an improved understanding of relationships across brain topics [40]. Augmented Reality (AR) is a potential technology for visualizing and comparing 3D brain representations [41]. AR allows neuroscientists to conduct an immersive investigation into 3D brain regions in a 3D environment, improving the intuitive exploration and comparison of disease patterns.

A neuroscientist, Harm Krugers[1], was interested in finding brain regions that are affected by at least two diseases. He believes that this information could help to find new insights about the relationship between diseases through affected brain regions, as well as new ways to treat diseases. To advance our understanding of complex brain diseases, we develop functionality to provide user-friendly access and clear explanations for comparing relationships among multiple diseases and brain regions. Our overall research question (RQ1) is: **How can we provide usable and explainable functionality for comparing relationships between different brain diseases and brain regions?** We identify functionalities that provide usable and explainable support for neuroscientists to compare relations between multiple brain diseases and regions. To answer this research question we want to know how to use AR efficiently to facilitate the exploration and comparison of disease patterns among different brain regions. This involves utilizing visualization of analyses derived from neuroscience literature. We conducted a study with participants with backgrounds in visualization and neuroscience to determine functionality usability and explainability. Having established the usability of comparing disease patterns among multiple brain regions through an analysis of neuroscience literature, we identify functionalities. We explored various functionalities, such as *Set Theory*, to highlight the similarities and differences in disease patterns. Harm Krugers reviewed these functionalities and recommended specific disease examples that illustrate relationships by examining their associated brain regions.

Having identified the required functionality, we need to develop and construct a suitable visualization to assess the efficacy of the identified functionality. Our second research question (RQ2) is: **How is our visualization usable and explainable to identify patterns in brain diseases that affect different regions?** To enhance the usability and explainability of our visualization in identifying patterns across various brain diseases, our approach is to integrate with established visualization techniques, such as those detailed in DatAR (e.g. Brain visualization, Co-occurrence explorer). This integration aims to provide an intuitive experience by assisting users in clearly identifying and comprehending the relationships between brain regions impacted by different diseases (we call this visualization version as **BasicCompare Version**) [41]. Fifteen participants from the fields of visualization and neuroscience evaluated an initial visualization to identify areas for improvement.

During the evaluation, we received feedback emphasizing the potential to further improve the visualization, facilitating **extending** the exploration and comparison of more than two disease patterns in brain regions as analyzed from neuroscience literature. Therefore, our third research question (RQ3) is: **How can we develop a visualization**

[1]https://www.uva.nl/en/profile/k/r/h.krugers/h.krugers.html

that aids in comparing disease patterns among affected brain regions, supporting the multiple relations between more than two different diseases and brain regions? We modified our visualization based on participants' comments. This modified version of visualization is called **MultiCompare Version** since it can support comparison between multiple relationships. Six participants, who also took part in the first study, assessed the updated visualization.

We follow the user-centered design approach in our work to guarantee that our work remains focused on providing real value to neuroscientists, closely aligning with their requirements and increasing the output's overall effect and success.

In Section 2, we explore how neuroscience literature analysis and AR visualization contribute to comparing disease patterns in brain regions.

Section 3 specifies the method that we used to identify the functions required for comparing disease patterns in different brain regions. In addition, we explain the visualization that we created using the functionalities indicated in the preceding section. After that, we explain the implementation of the provided functionalities and visualizations, in section 4.

Section 5 details the evaluations undertaken by visualization experts and neuroscientists.

Section 6 examines the feedback and insights gained, which result in additional suggestions and improvements to our visualization.

Finally, in the last two sections (7 and 8), we present our opinion on the gathered results, drawing together the findings from our studies and providing the potential pathway for future research.

3.2. Related Work

We describe 2D and 3D visualization techniques to help neuroscientists visualize, analyze, and support comparing disease patterns in affected brain regions (Section 3.2.1). We discuss the use of Augmented Reality (AR) for its ability to be used for 3D visualization of brain models, discussing its benefits and potential to improve the analysis and comparison of disease patterns (Section 3.2.2). These discussions are related to our first and second research questions on providing usable and explainable support for comparing relationships between multiple brain diseases and brain regions.

3.2.1. 2D and 3D Visualization Techniques in Neuroscience

Visualization tools in neuroscience support the showing of affected brain regions by diseases. They offer a medium through which to understand the relationships between brain regions and the diseases that affect them. As an example, Neurosynth enables users to explore literature based on keywords and presents the relationship between the keyword and brain regions using 2D representations of various brain model views. To compare two or more keywords, researchers visually compare plan views of brain visualizations. 2D visualizations may not capture the complex spatial relationships within the brain's 3D structure, potentially hindering a detailed understanding of interconnected regions. We explain more information in subsection 3.2.2 to explain how other mediums are beneficial in neuroscience topics visualization.

3D Visualization Techniques: Three-dimensional visualization techniques provide a comprehensive view of the brain's structure, enabling an in-depth exploration of the spatial relationships between distinct brain regions and their associated diseases. A 3D representation of brain topics may allow researchers to discover patterns and relationships that may be hidden in 2D visualizations.

To compare the relationships between brain diseases and brain regions, researchers often analyze brain images (see Figure 3.2) [7, 8]. These studies typically employ 3D brain models to depict these relationships and map related topics onto a 3D brain model which is presented by a 2D medium (e.g. screen, paper). However, such visualizations may not fully capture the depth of the brain, which is essential for a complete understanding of brain regions. Therefore, using visualization techniques that can accurately represent the complex structure of the human brain may be beneficial for understanding relationships between brain topics.

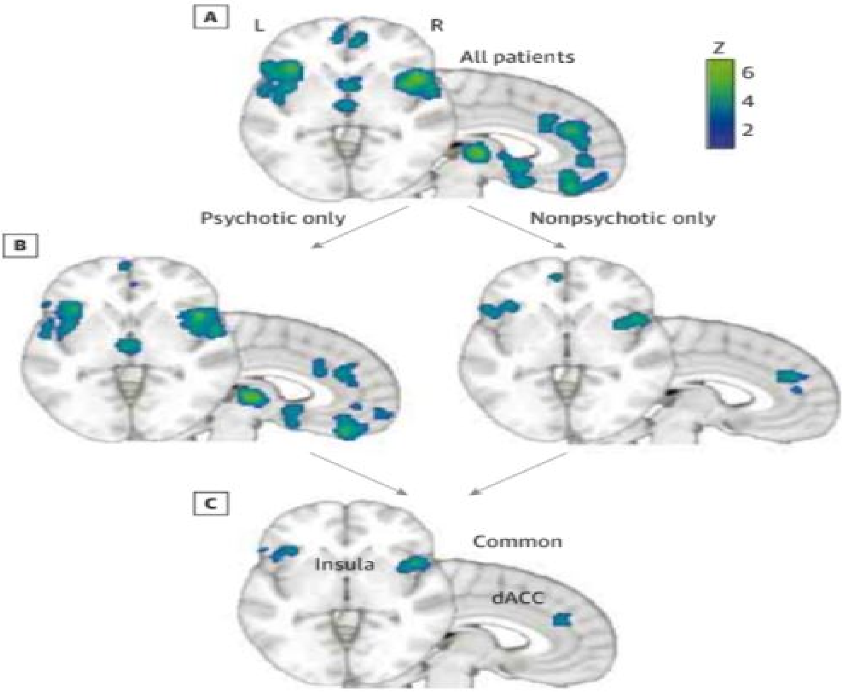

Figure 3.2: Comparative Analysis of Brain Regions Impacted by Psychotic Disorders Versus Nonpsychotic Conditions. The green-blue patterns represent the decreased gray matter of the brain. [A] Union, affected parts for all of the patients, [B] left for patients with condition (psychotic), right for patients without condition, [C] Intersection, shared parts for all of the patients. Image is taken from [7].

To solve the clutter and occlusion problem of showing 3D visualizations in 2D, We want to see how the 3D environment works better for these types of visualizations.

3.2.2. Augmented Reality Visualization in Neuroscience

We look at how augmented reality can help neuroscientists compare different brain disease patterns in affected regions to identify relationships between topics.

AR/VR for 3D Brain Visualization: Brain imaging has improved our understanding of brain models by allowing for precise mapping of neural activity, showing complex patterns of relationship between different brain regions, and allowing for the detection of functional and structural defects associated with various neurological conditions [42]. Despite the difficulties in displaying identified brain networks due to the integration of multiple features into a single image of brain geometry [31, 43], Augmented Reality provides solutions for a variety of neuroscience applications [44], improving the visualization and comparison relationships between brain topics. The application of AR/VR technologies in neurology has been utilized to create 3D models from head MRI and CT scans [45]. Using virtual reality was used to display the 3D anatomy of the brain [46], it can provide better techniques for presenting and comparing affected regions with different diseases.

NeuroCave is a VR platform developed for neuroscientists to explore and analyze relationships between brain regions [31]. By examining NeuroCave's features, design decisions, and outcomes, we assess immersive environment value in finding and visualizing brain topic relationships. The adoption of immersive VR environments such as NeuroCave highlights their effectiveness in offering intuitive research experiences, thus deepening insights into brain networks. This approach is somewhat similar to our objective of providing usable visualization of relationships between brain disease and affected brain regions in neuroscience, emphasizing clarity and consistency in our examination. Use Augmented Reality (AR) technology to develop an intuitive environment for comparing relationships between brain diseases and brain regions they affect.

3.2.3. Exploring Relationships between Topics in Neurosciences Literature: DatAR

We describe the previously implemented functionalities of the DatAR tool in our work. DatAR facilitates (1) concurrent investigations for examining related brain diseases and regions, and (2) the 3D visualization of brain regions. Analysis tools, called widgets, can be used for tasks such as querying, data export, visualization, and manipulation.

The widget "co-occurrence explorer" (cube 1) in Figure 3.3, found the results of affected regions by Depressive and Anxiety from the PubMed repository if they appeared in one sentence of publication. The widget "Brain model" (cube 2), highlights the affected regions in red spheres.

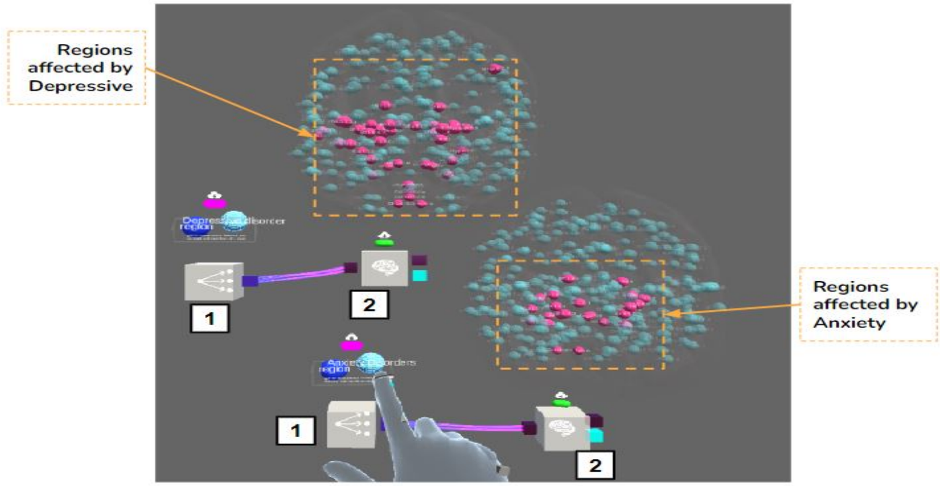

Figure 3.3: First-person view showing the visual comparison of regions related to two different diseases (Top, brain regions affected by *Depressive*. Down, brain regions affected by *Anxiety*).

3.3. Method

We follow a user-centered design approach, where we first identify the representative neuroscience task(s) for which we develop the comparison functionality and visualizations. Having identified representative tasks (subsec 3.3.1), we determine the functionalities to support them (RQ1, subsec 3.3.2). We outline the functional design requirements for three selected functionalities based on *Set Theory (Intersection, Union and Difference)*. Subsequently, we argue the suitability of a specific design to meet these requirements, evaluating the appropriateness of the task as detailed in (subsec 3.3.3).

Based on the user-centered design approach, we are keen to gather feedback that would allow us to provide detailed and rich descriptions. So, the qualitative content analysis to examine the transcribed data (interviews) would be used. Also, we have to statistically analyze the participants' perceptions of the functionality usability (using the System Usability Scale). We also want to show which features influence participants' intention to use our provided comparison functionality by using the Technology Acceptance Model (TAM).

3.3.1. Identify Representative Task

We identify a task to understand what to provide as the functionality of our tool. The task of comparing brain regions affected by different diseases is critical to identify possible relationships and differences in how diseases affect the brain regions. We consider two diseases - Depression and Anxiety, as suggested by neuroscientist, Harm Krugers. These diseases frequently appear together in literature (call them semantically similar diseases), showing a possible similarity in affecting brain regions. However, the number of identified relationships between these two diseases and regions within the neuroscience database (PubMed) is markedly different. This scenario inspired the development of a **"Comparison Task"**, where a neuroscientist aims to identify the patterns through similarities and differences in the brain regions affected by diseases.

Task #1: Identifying Shared Affected Regions by Two Semantically Similar Diseases: To identify shared brain regions affected by both depression and anxiety. This process involves looking at evidence to identify overlaps in the affected regions, emphasizing similarities in the diseases' impacts on the brain. This could help in understanding the common patterns underlying different diseases.

Task #2: Identifying All Affected Regions by Two Semantically Similar Diseases: To list all brain regions impacted by depression and anxiety, regardless of whether they are affected individually or together. This tries to construct a complete list of afflicted regions, offering a wide picture of the diseases' effects on brain regions.

Task #3: Identifying Differences Between Affected Regions by Two Semantically Similar Diseases: To identify brain regions that are specifically affected by either depression or anxiety. This work focuses on discovering differences in how diseases affect the brain, showing particular ways that each disease may target. This can be important for developing individualized treatments for each disease.

3.3.2. Comparison Functionalities

The task of comparing brain regions affected by different diseases requires a comprehensive strategy to enable an in-depth investigation. Using the example of Depression and Anxiety again, while they may have semantic similarities in the literature, the specific regions of the brain they affect may differ, needing a detailed comparison to highlight these differences.

To meet this need, we propose three fundamental functionalities based on **Set Theory** that will allow for a meaningful comparison of diseases' impact on brain regions. Figure 3.4 shows these functionalities, which are further detailed below:

Intersection Functionality: This function allows users to identify affected brain regions by both diseases. In the Depression and Anxiety example, this functionality shows affected brain regions in the middle of the brain.

Union Functionality: This functionality determines affected brain regions by either of the diseases.

Difference Functionality: This functionality determines affected brain regions of one of the diseases that are not in another.

These three functionalities provide a structured and user-centered approach to finding relationships between diseases and brain regions. By implementing these comparison functionalities, we aim to support neuroscientists in obtaining new information about the relationships between diseases and how they are similar in terms of affected brain regions. This information would be used as a new research or disease treatment area.

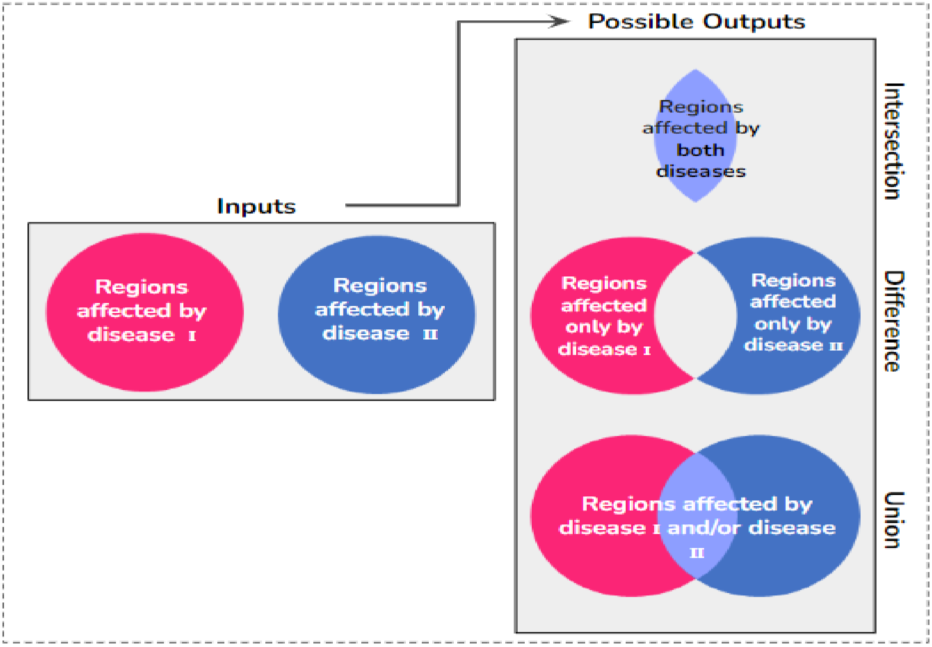

Figure 3.4: Intersection, difference, and union functionalities (Set Theory).

3.3.3. Visualization Design

Having identified the three comparison functionalities in sec 3.3.2, we explain the requirements and design rationale we used to design first an initial visualization (**"BasicCompare Version"**, sec 3.3.3) and then later an improved visualization (**"MultiCompare Version"**, sec 3.3.3).

Visualization Design Requirements (for Basic Comparison):

In previous work, we implemented visualizations and interactions to present 3D brain models and relationships between diseases and affected regions (chapter 2). These can be used for comparing relationships and finding disease patterns of affected regions (we call this a comparison task). To design visualization support for comparison tasks, we identify several design requirements (DR).

DR #1: Visually compare affected regions by diseases

The DR1 is taken from prior research, which focused on examining relationships between diseases and associated brain regions, where participants expressed the wish to observe and compare these relationships simultaneously [41]. To compare two 3D brain models at the same time, they must be displayed side by side and have the same position, rotation, and size, Figure 3.5. The 3D brain models showing regions affected by different diseases can be compared visually [47].

DR #2: Identify the location of affected regions

To compare affected regions' locations to their actual locations inside the brain, users need to see both the affected and unaffected regions at the same time, Figure 3.5.

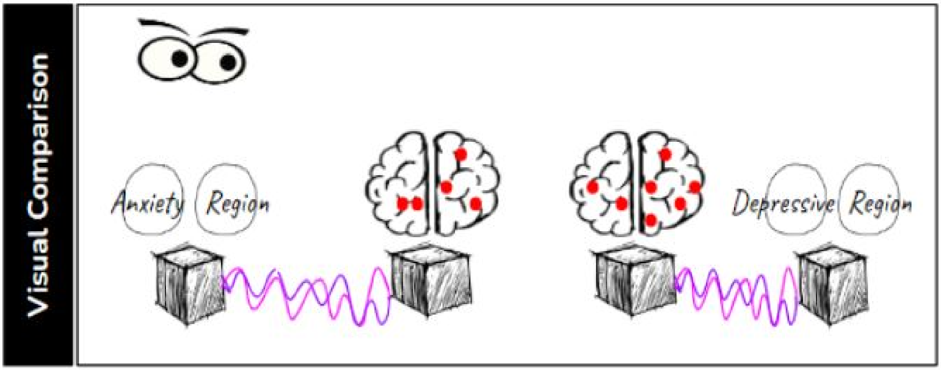

Figure 3.5: Our initial design provides an AR environment to present relationships between Depressive (In our repository, Depression is called Depressive) and Anxiety and the affected regions in 3D brain models (The figure is for explanation and does not represent the actual implementation).

DR #3: Improve visual comparison with filtering support Visual comparison of 3D models is a potentially useful initial step. However, when dealing with many relationships, visually identifying similarities or differences among affected regions becomes challenging. To facilitate a clearer visual comparison, filtering options can reduce cognitive load by minimizing visual complexity and enabling users to focus on specific relationships of interest, Figure 3.6.

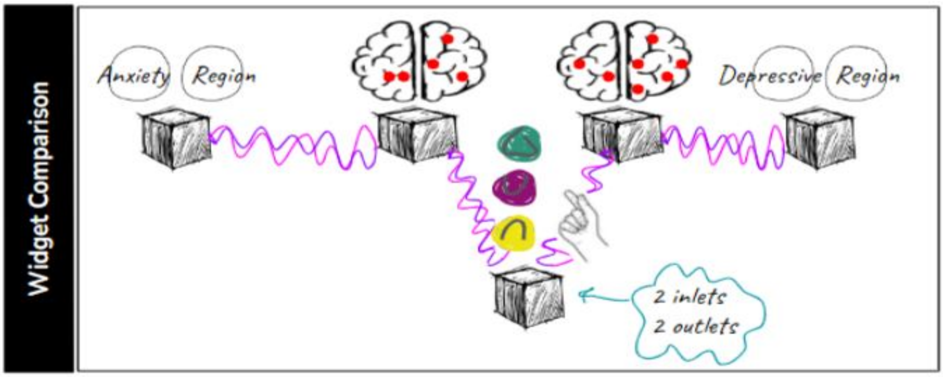

Figure 3.6: Our initial design of BasicCompare functionality filters the affected regions based on intersection or union or difference function (The figure is for explanation and does not represent the actual implementation).

DR #4: Provide an explainable comparison Using filters to refine the displayed relationships helps to achieve clearer results. While visual comparison is still required to recognize these relationships, offering additional aid through textual information might be useful. We have to offer an explainable design that can validate the comparison understanding by checking the shown affected regions. By attaching the names of the displayed relationships in text form, we provide an option for users to validate the visual discoveries they get from filtering. This textual detail allows users to validate their observations, which improves the comparison process, Figure 3.7.

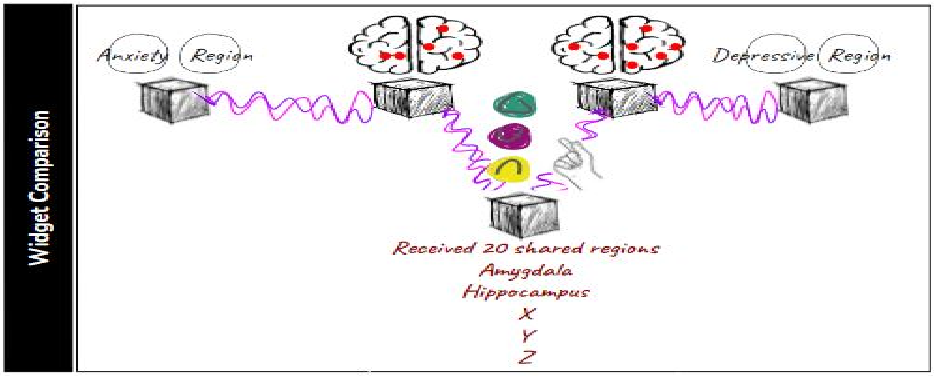

Figure 3.7: Our initial design of BasicCompare functionality shows the affected region names in text based on intersection or union or difference function (The figure is for explanation and does not represent the actual implementation).

All of these visualization designs are considered in our implementation and could be used in the comparison process. It depends on users' tasks and goals to decide how many details and support they need.

Visualization Design Requirements (for Multi Comparison):

The Comparison functionality overwrites the affected regions on the initial ones in two brain visualizations. This means the user can not reach the affected regions by each of the two diseases. Additionally, both brain visualizations show the result of comparison functionality which means they show the same result which is useless.

DR #5: Ease of Visualization and Comparison

Enhance the user experience and provide practical functionality. Comparing the relationships between diseases and their affected regions should be achieved with minimal head movements, ensuring the interface is intuitive and does not cause discomfort. Streamlining the comparison process allows users to focus more on the analysis and less on navigating the interface. Ease of Visualization and Comparison means to put important objects that should be seen together in the same view of the used medium. For example, when users want to compare two brain models, they should be close enough to conduct information.

Revisualization of functionalities

Since our used medium (HoloLens 2) has a wider horizontal view in comparison with a vertical view, we have to show the needed buttons for each function in an x-axis. So, users can see all of the buttons in one view.

Show the result in a separate brain model

In the BasicCompare version, when users asked for the Intersection, Union, and difference functions, both brain models changed to show the results. Since the highlighted results were the same for the Intersection and Union functions and to decrease the head movements for comparing the visualizations, we consider a separate brain model to present the related regions as results, Figure 3.8.

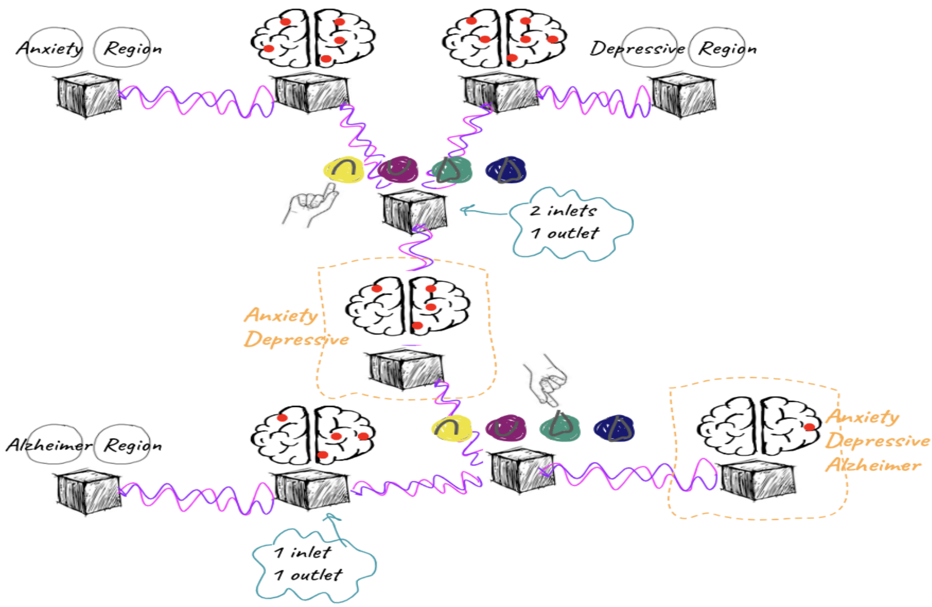

Figure 3.8: Our initial design of MultiCompare functionality filters the affected regions based on pressed controls; intersection, union, and difference (The figure is for explanation and does not represent the actual implementation).

3.4. Implementation of Visualization Design

We implement the comparison functionality as an analysis tool in the immersive environment; called Widget. The widget sends data to another widget through an outlet and receives data from an inlet. After applying the design rationales for the comparison functionality (BasicCompare), we improved the visualization design in the MultiCompare version. For both versions, we have to use different amounts and sorts of the widgets' outlet/inlet, Figure 3.9 and 3.10. The implemented Basic Compare functionalities are shown in the following Figures; 3.11, 3.12, and 3.13.

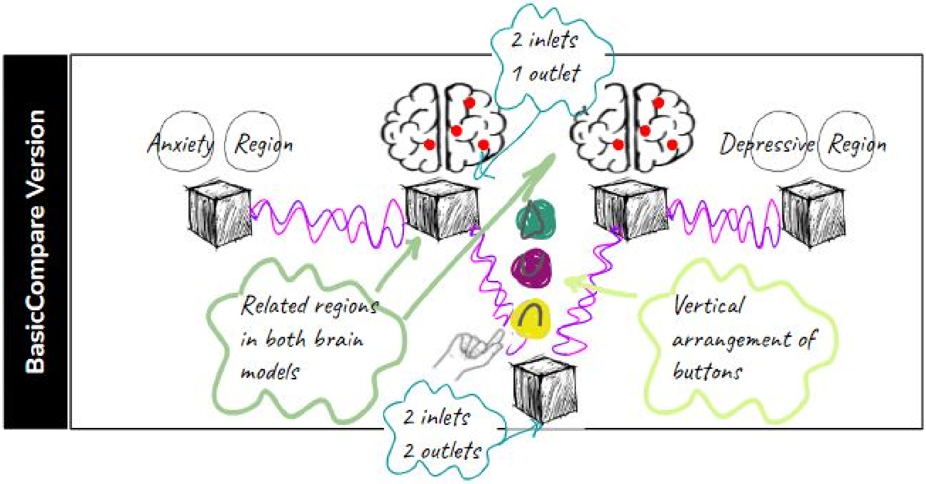

Figure 3.9: "BasicCompare Visualization" is the first version of the tool for the comparison task (The figure utilized is purely for mock-up purposes and does not represent the actual results).

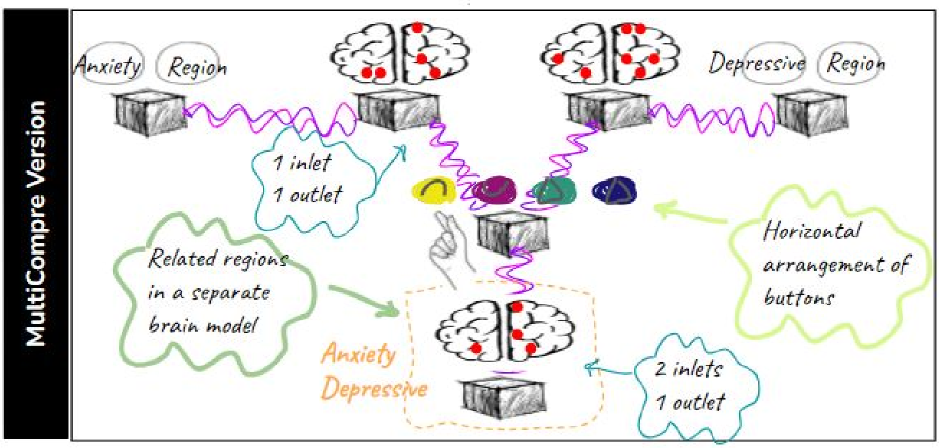

Figure 3.10: Improvements from the previous version. "MultiCompare Visualization" is the extended version of the tool (The figure utilized is purely for mock-up purposes and does not represent the actual results).

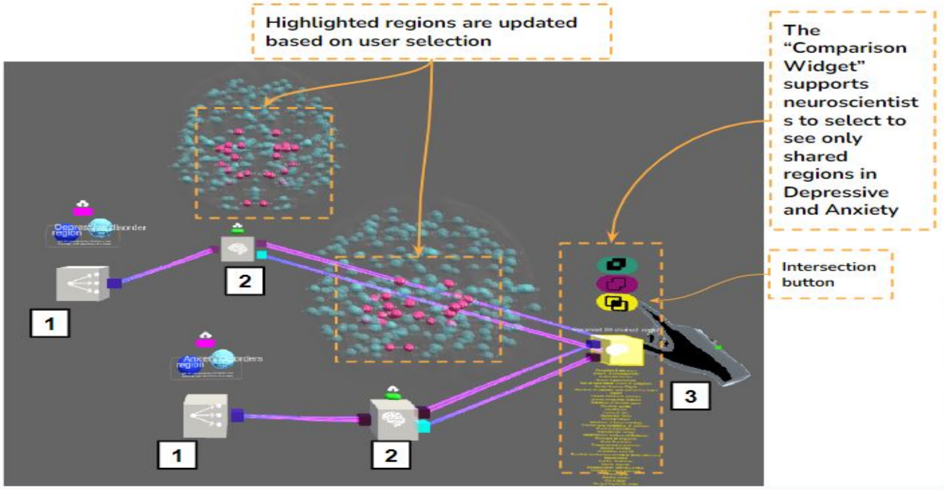

Figure 3.11: First Person View showing a user interacting with the "Comparision Widget" (yellow control); the icon 3, works as the Boolean operation of "intersection".

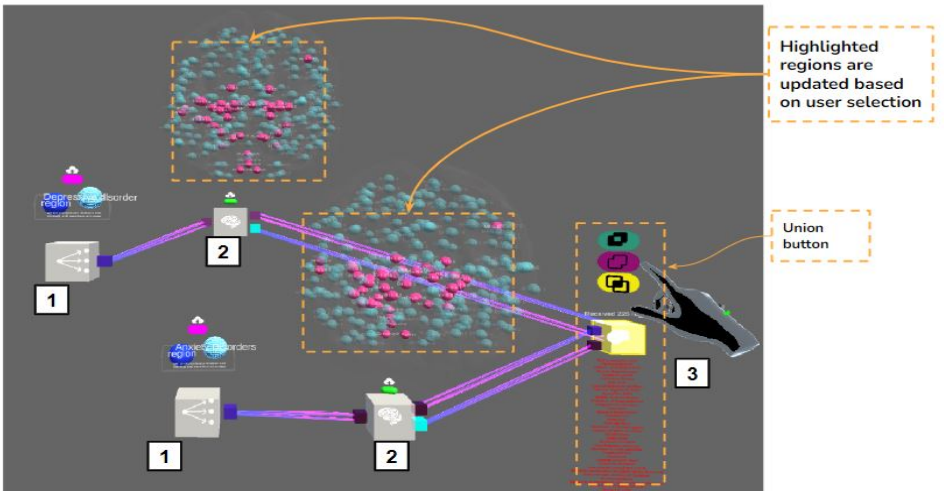

Figure 3.12: First Person View showing a user interacting with the "Comparision Widget" (pink control); the icon 3, works as the Boolean operation of "union".

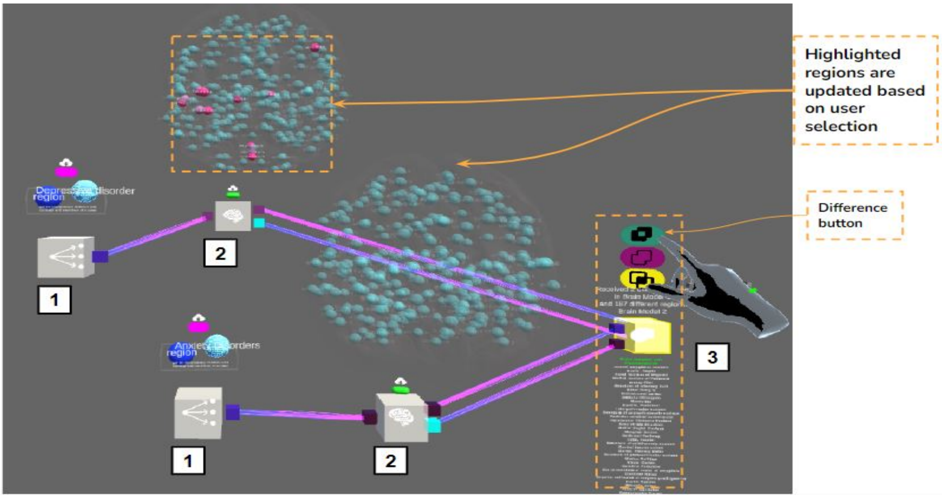

Figure 3.13: First Person View showing a user interacting with the "Comparision Widget" (green control); the icon 3, works as the Boolean operation of "difference".

The design of the MultiCompare version potentially supports the comparison of multiple brain models. This valuable feature has emerged solely through design modifications, without initial consideration in the original design. The design facilitates the understanding of complex relationships between brain regions associated with diseases. These relationships can grow and act like a network of edges and nodes. However, the evaluation conducted on this version of the tool has followed the display criteria set for the initial version, Figure 3.14.

The visualization uses spheres to denote various brain regions, set within a transparent outline of the entire brain, making it a salient feature for conveying complex neuroscientific information.

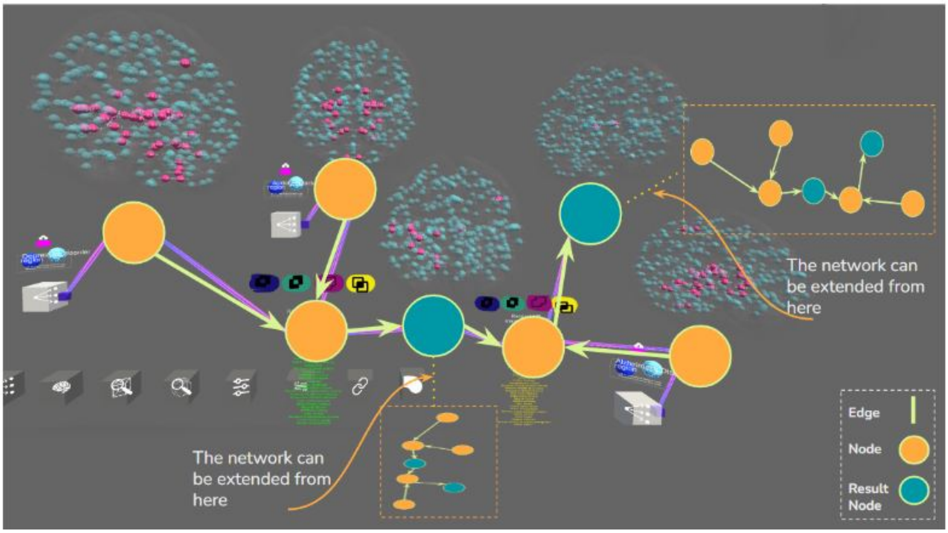

Figure 3.14: The compatibility of MultiCompare version to make a network of different comparing the effect of diseases on regions.

3.4.1. Data Source

Insights into the relationships between brain diseases and regions can be obtained through the analysis of neuroscience literature. We use the Knowledge Graphs of Brain Science (KGBS) available from Triply [2]. The repository contains co-occurrences of topics (including brain regions, brain diseases, and other brain topics) mentioned in sentences in the abstract and title of publications. The ten thousand publications analyzed for this study were gathered from neuroscience-related articles available on PubMed[3].

3.4.2. Apparatus

Our Optical see-through head-mounted displays (OST-AR) visualization tool was developed and built using Unity3D (v2020.3.15f2) using the MRTK package (v2.7.0) and was running on a HoloLens 2 head-mounted display. The attached C# code to Unity is stored as a separate branch of the main DatAR tool in the GitLab of Utrecht University.

3.5. Evaluation

We evaluate the BasicCompare and the MultiCompare functionalities to measure the functionality/visualization usability and explainability based on our research questions.

[2]Knowledge Graphs of Brain Science in Triply https://krr.triply.cc/BrainScienceKG/-/queries/Brain-Region—Brain-Disease/1

[3]https://pubmed.ncbi.nlm.nih.gov/

3.5.1. BasicCompare Version

We conducted qualitative and quantitative evaluations involving two groups of participants. Six neuroscientists and nine data visualization experts assessed the usability and explainability of the comparison functionality (RQ1) and the visualization aspects (RQ2). Visualization participants were not required to possess knowledge of neuroscience, as (1) the comparison functionality results apply to all researchers, and (2) we explained the neuroscience literature case study to participants before they carried out the task.

To assess effectiveness compared to the traditional methods that researchers use for the "Comparison Task," we posed questions based on (1) Topic-based discovery and (2) Literature-based discovery. Topic-based discovery involves exploring relationships and comparing results using our provided functionality, while literature-based discovery focuses on identifying relationships by examining available literature in online resources.

Participants

Six neuroscientists who had an understanding of neuroscience literature and were able to evaluate the comparison functionality concerning their neuroscience research goals participated (P1-P6).

Nine visualization experts with experience in reviewing literature, but not neuroscience literature with an understanding of the literature exploration task participated (P7-P15).

The sessions were in-person and they used the same comparison functionality implemented in the HoloLens 2 headset.

Tasks and Procedure

Each session of approximately an hour started with an introduction about the way that neuroscientists explore and compare relationships between brain-related topics (see subsection 3.3.2) and continued with an introduction to the tool (see subsection 3.2.3) (totally 10 minutes).

Step 1 - Topic-based discovery: For this study, to minimize the time required from participants, the experimenter created an immersive environment for each participant in advance. When participants put on the headset, they saw a visualization of the brain disease Depressive and the regions affected by it to the right of their field of vision (Figure 3.15, right-hand brain). To the left of their field of vision, they saw a visualization of the brain disease Anxiety and the regions affected by it (Figure 3.15, left-hand brain). The experimenter explained the visualizations, Figure 3.15, and asked the interview questions during the task using the think-aloud technique.

Step 2 - Literature-based discovery: Also, after using the functionality, we asked them to use the laptop and find and compare the relationships between topics by using online resources in the literature.

At the end of these steps, participants filled in an online post-questionnaire (SUS Questionnaire).

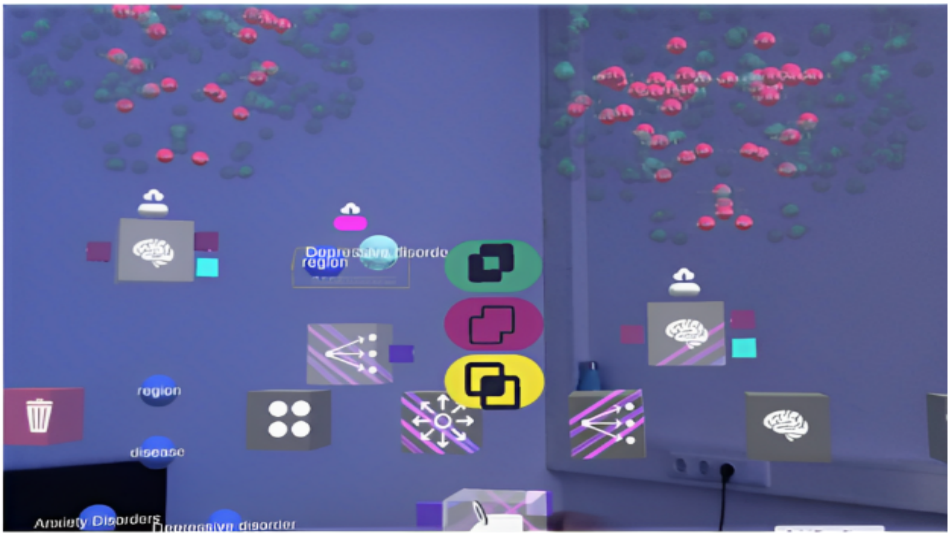

Figure 3.15: First-person view of an example task setup. Participants could visually explore which brain regions and in which area of the brain (e.g. front, middle, or back) are related to the selected diseases. “Comparison Widget” could help participants limit the results and make conclusions.

3.5.2. MultiCompare Version

We ran a quantitative evaluation to evaluate our functionalities in the manner of updated visualization, we asked 6 data visualization experts to do the study. We measure how participants perceive the visualization usable by the System Usability Scale (SUS) method.

Participants

Six out of nine of our visualization experts from the first version study (BasicCompare) participated in this study. They reflected on their experience, their understanding of the functionality, and their observations on the new visualization.

Tasks and Procedure

To gather data, we administered a video survey. We introduced the survey to participants as a means of "how we support neuroscientists to compare multiple visualizations of the relation between brain diseases and regions in an AR environment". Then they watched a recorded video (which took an average of 6.47 minutes to finish) of the MultiCompare version interactions and functionality captured through Unity. We asked participants to rate the following statements about the MultiCompare version.

Table 3.1: User statements on Functionality

Statements
Extendability feature usefulness
Functionality complexity
Comparison widget for multiple relationships comparison
Overall design
Comparison widget usefulness
Comparison widget prior knowledge
Visualization clarity
Result informativeness
Design user-friendliness
Features of functionality easy to understand

Participants also rated the sixteen bipolar adjective pairs on the functionality of the new version (attached in Appendix A.2).

3.6. Results

To answer all of our RQs, qualitative and quantitative results are categorized based on the usability, explainability, and visualization aspects. We used Likert scale items and bipolar adjective pairs to measure participants' responses, evaluating the usability of the functionality we offered (Figure 3.22). To better analyze these visualizations and reflect the diversity of our sample, we looked for variances in responses among subgroups, specifically neuroscientists and visualization experts.

3.6.1. Results of Basic-Compare Functionality

This section concentrates on participants' insights on the usability, explainability, and visualization aspects of our initially developed functionality, Basic-Compare.

Specialized exploration tools and the time required for Literature-Based Discovery

We asked our participants about their use of specialized exploration tools for identifying relationships between topics. Furthermore, we explored how much time they need to find and compare all the relationships when utilizing these tools.

The majority of participants (8 out of 15) primarily utilize keyword searches in search engines to explore resources and extract information, as illustrated, Figure 3.16, by the word cloud. This information is gathered from participants' opinions on the quantitative question; "Do you use any specialized tools (including automated methods and custom user interfaces), services, data sets, or procedures to explore or review academic literature? Could you briefly describe these?". However, a neuroscientist (P15) also mentioned alternative online platforms, such as Neurosynth[4], which serves as a

[4] https://neurosynth.org/

specialized search engine in the neuroscience field.

The time required to find relationships through literature and compare results ranged from several hours to an entire day, depending on the researcher's experience and the chosen topics for identifying relationships. This information is based on the answer to the question, "How long do you need to find which parts of the brain are most affected by two brain diseases (Depression and anxiety) by using online literature?" by fifteen participants.

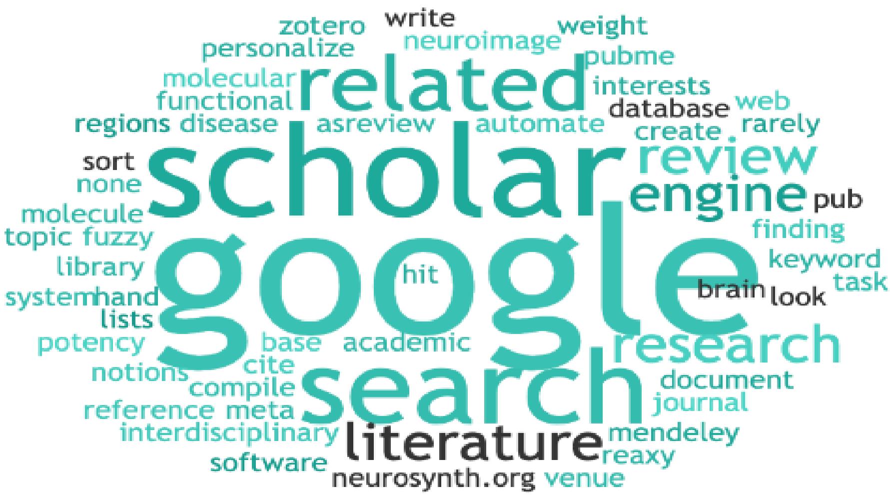

Figure 3.16: A word cloud of specialized tools (including automated methods and custom user interfaces), services, data sets, or procedures to explore or review academic literature based on responses from all 15 participants. The size and brightness of the words indicate their frequency of occurrence in participants' answers.

Usable and Explainable Functionality and Visualization for Topic-Based Discovery

Brain Visualization Usability. Six neuroscientist participants found the brain visualization usable, allowed them to easily identify brain regions. They also considered the use of different colors to highlight related and unrelated regions as an effective method for presenting relationships between diseases and regions, Figure 3.17. Visualization experts shared similar views, with only one expressing uncertainty regarding the optimal choice for displaying relationships by highlighting regions.

More than half of the participants (N=8) positively highlighted the use of the brain's shape to represent different brain regions.

In contrast, a concern was raised by participants experiencing depth-perception difficulties. They reported challenges in distinguishing spheres that are positioned at the same viewpoint. To improve their understanding of brain visualization, they suggested introducing a feature that enables users to customize which part of the brain is visible.

This would aid them in focusing on individual brain regions without the interference of overlapping spatial locations.

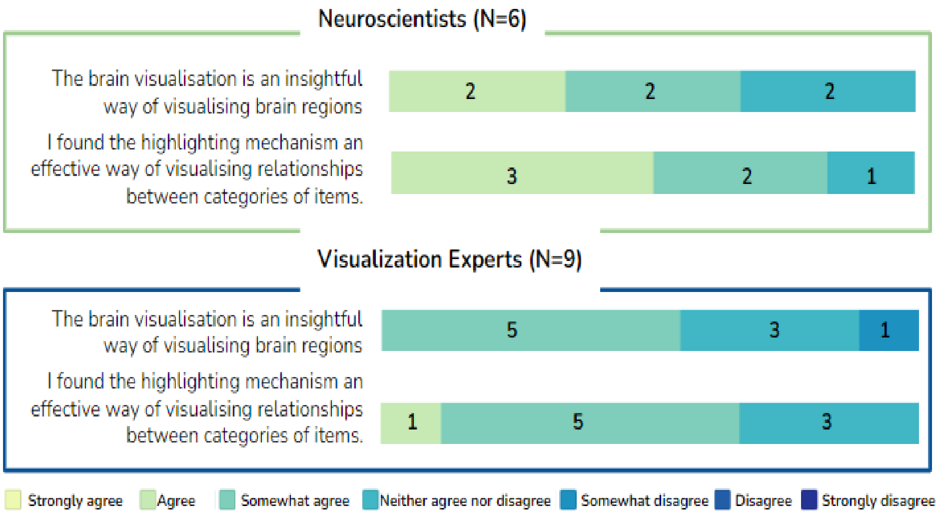

Figure 3.17: Participants' rating of highlighting the affected brain regions by disease (Figure 3.15).

Comparison Widget Usability. Participants found that visually comparing two separate brain visualizations to identify common regions required some mental effort to determine shared areas. However, using the widget allowed for easier comparisons. Among the three controls, the "Intersection control" was deemed the most useful, while the "Union control" was considered less useful by most of the participants (N>10). Despite this, one neuroscience participant mentioned that the "Union control" could still be beneficial for specific research purposes.

The opinions on providing list of brain region names as shown in the text (Figure 3.11, 3.12, 3.13 - widget icon 3: names are in the text under the widget) to support the visualization of highlighted regions were mixed among neuroscience participants. While some found it useful, others disagreed. Although the concept behind the text for showing the results was helpful, participants did not consider the visualization (list of region names) to be practical since we showed the long list. Based on two neuroscientists' feedback, we understand that in the neuroscience field, certain regions may not be of interest to researchers, or only a few researchers may be interested in them. Thus, it is beneficial to have a list of the names of affected regions, which can be sorted and categorized by region. This could be automated or user-controlled, Figure 3.18.

Comparison Visualization Explainability. All of the participants successfully compared brain visualizations to identify regions affected by multiple diseases, finding the 3D immersive environment facilitated clear and comprehensible comparisons. When asked about the interesting or meaningful aspects of the visualization, neuroscientists

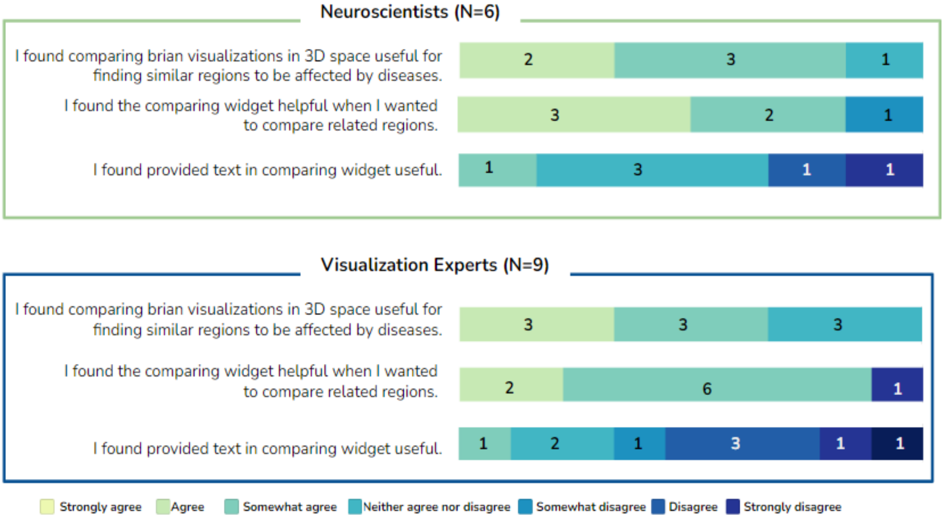

Figure 3.18: Participants' ratings of the comparison functionality (figures 3.11, 3.12 and 3.13).

provided technical information regarding the displayed results such as scrolling function or limited regions based on their interests. They discussed the positions of regions in the brain, noting that anxiety mostly affected central regions distant from advanced human brain regions. While these results were expected from neuroscientists, the visualization allowed for more usable comparisons than traditional methods.

Some visualized results prompted neuroscience participants to further investigate the findings due to their novelty and interest [N5, P6]. Two participants suggested a comparison function even before being shown the one we had implemented, expressing a desire to see highlighted regions affected by multiple diseases [N3, P5]. A participant familiar with neuroscience literature observed that the presented relationships were supportive, as papers typically only reference relationships textually without visually depicting the information within the brain [P8]. The 3D visualization helped participants, especially non-neuroscientists, detect patterns in the brain, such as the symmetry of anxiety-affected regions and the predominantly right-sided regions affected by depression, Figure 3.19.

All of the neuroscientist participants had suggestions for improvement in the explanations provided. Access to the dataset was a common request, as participants wanted to validate the relationships found. They also requested improvements in the color coding of brain models, suggesting that different colors for each lobe could help identify the location of affected regions. Participants effectively compared similarly affected regions in the brain visualizations, but providing information about positive or negative relations (based on the meaning of the original sentences) and the number of papers mentioning the relationships could further enhance the gathered relationships.

Comparison Widget Explainability. After introducing the "comparison widget" and

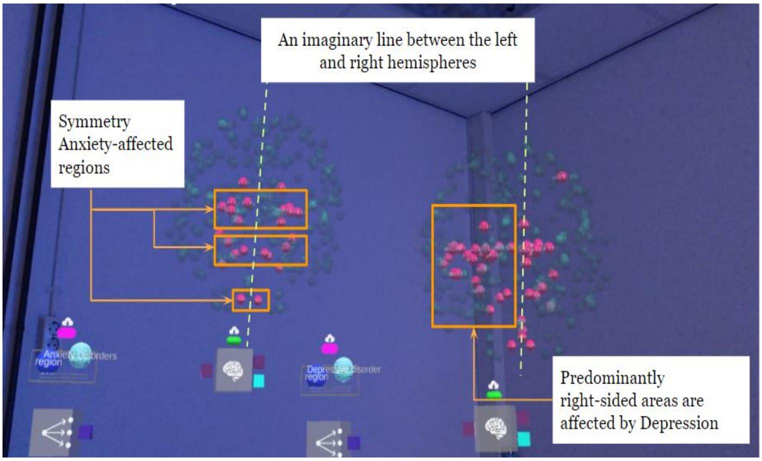

Figure 3.19: Discoveries by visualization experts showing the brain regions impacted by Depression and Anxiety. The view of the brain is from the front.

explaining its features, we ensured that participants understood the functionality and were thus prepared for the remainder of the session. Visualization expert participants suggested improvements in interaction, such as visual feedback when for a function to confirm their input. Currently, pressing a function control changes the highlighted regions based on the function. Still, due to the limited field of view (FoV) of the HoloLens, participants preferred receiving feedback on the appearance of the controls before looking at the highlighted regions. Moreover, they proposed using different color coding for the results of each function, as the current color for affected regions is red.

With the comparison widget in place, participants correctly and accurately identified common regions affected by both depression and anxiety when asked. They used the "Intersection control" to observe the similarities in terms of regions affected by both diseases.

Participants' experiences in AR/VR and exploring literature

We asked participants about their previous experiences in AR/VR since these can lead to different feedback on the functionality. Among the neuroscientist participants, three had prior experience with only Virtual Reality technologies. These neuroscientists generally possessed extensive experience in conducting literature reviews. Over half of the visualization experts were familiar with AR/VR technologies, and one had some understanding of neuroscience and brain-related subjects. All of the participants concurred that traditional literature exploration poses a significant challenge for researchers, and it is not consistently enjoyable.

Rating Regarding the Desired Media to Display

Based on the SUS Method, the ratings indicate that approximately none of the neuroscientists are keen on abandoning their traditional methods for exploring literature to compare relationships between diseases and regions. Additionally, they did not find the on-screen (2D) visualization of relationships satisfactory. However, they showed a preference for AR visualization over VR. In contrast, visualization experts rated VR more favorably than AR and screen visualizations. Visualization experts appeared more inclined to use traditional literature exploration methods compared to neuroscientists, Figure 3.20.

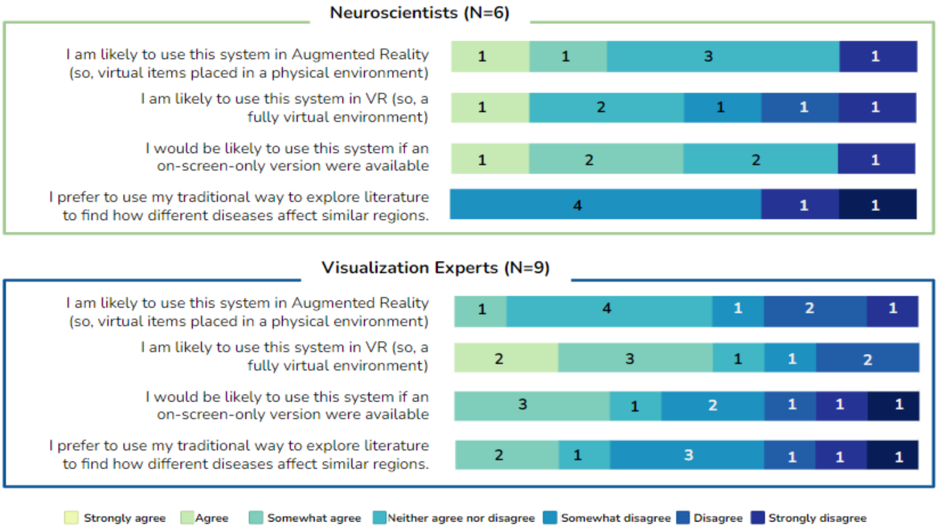

Figure 3.20: Participants' ratings of the medium used for displaying relationships.

Rating Regarding the Usability

The findings suggest that the functionality is effective for comparing relationships, but it is not yet fully optimized for daily use. One possible reason for this perception could be the complexity associated with using the AR environment since it is a new technology for most people and interaction is not always fast and smooth. Further refinements and enhancements to the user experience could potentially address these concerns and make it more suitable for routine application in the research process. Additionally, providing comprehensive training and support materials for users may contribute to an increased sense of confidence and ease when working with the AR environment. The feedback captured in Figure 3.21 underlines our commitment to ensure it meets the efficiency and user-friendliness standards required for frequent use in research contexts, as indicated by the responses from both neuroscientists and visualization experts.

Comparing the functionality's general features

We assessed both positive and negative responses to statements from the Technology Acceptance Model (TAM) about the features, Figure 3.22. Among neuroscientist participants, the "Interactivity" feature received the highest rating, while the "Maturity" feature scored the lowest. Visualization experts highly rated the functionality to be interactive and meaningful; however, they also reported it as somewhat confusing and

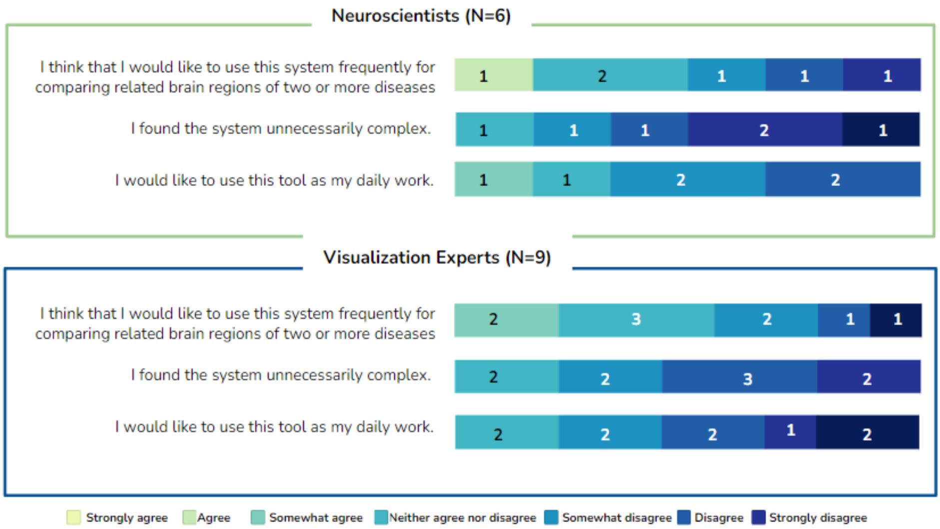

Figure 3.21: Participants' ratings of the usability of the comparison functionality.

not as simple to use.

Neuroscientists perceived the comparison functionality to be clearer, more practical, simpler, faster, more exciting, and more interactive compared to visualization experts. The disparity in opinions was particularly noticeable for the "Clear" feature. Conversely, visualization experts considered the functionality more informative and meaningful than the neuroscientists. These contrasting perspectives highlight the importance of addressing the diverse needs of users from different backgrounds when refining the functionality for broader applications in academic research.

3.6.2. Results of Multi-Compare functionality

The "MultiCompare Visualization" supports multiple comparisons between diseases and affected regions. To statistically address our third research question, we calculate the mean scores for criteria such as extendability, comparing widget support, comparison widget usefulness, visualization of topics relations, design informativeness, and provided features (Intersection, union, difference) are relatively high, ranging from 14 ± 1 to 15 ± 0.5 (the range of scores are between 11 for min and 17 for max), Figure 3.23. These scores indicate that users appreciate the tool's capabilities and design elements in assisting with their tasks.

However, there are some aspects where the functionality can be improved. The mean scores for criteria related to complexity, design intuitiveness, and user-friendliness are lower, ranging from 14 ± 1 to 15 ± 1. These scores suggest that some users found the system unnecessarily complex and the design less intuitive and user-friendly than desired. Moreover, the criterion "Working with the Comparison widget needs Pre-knowledge" has a mean score of 15 ± 1, which indicates that users believe some prior knowledge is necessary to work effectively with the Comparison widget.

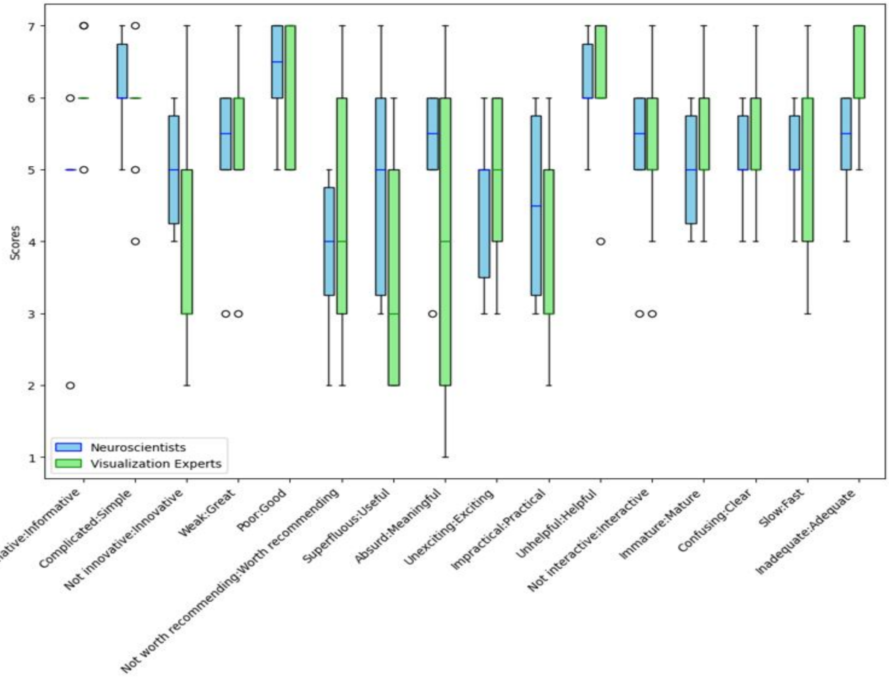

Figure 3.22: Average mark for bipolar adjective pairs (negative-positive) for 6 neuroscientists and 9 visualization experts; the Technology Acceptance Model (TAM). The small circles are outliers.

The standard deviation and variance values are relatively high in complexity, design intuitiveness, and user-friendliness. Users found the MultiCompare version useful and valuable.

3.6.3. Comparing Bipolar adjective pairs for BasicCompare and MultiCompare

The evaluation of the BasicCompare and MultiCompare functionalities involves various criteria, each rated on a scale, where we compute the minimum, maximum, mean, standard deviation, variance, number of responses, and total scores for each. See Figure 3.24 and 3.25 for a comparison of these results. We sorted the features based on scores for both versions.

MultiCompare version generally takes the maximum scores (score 7) for most of the features, suggesting greater variability in user responses for several criteria, such as informative and helpful.

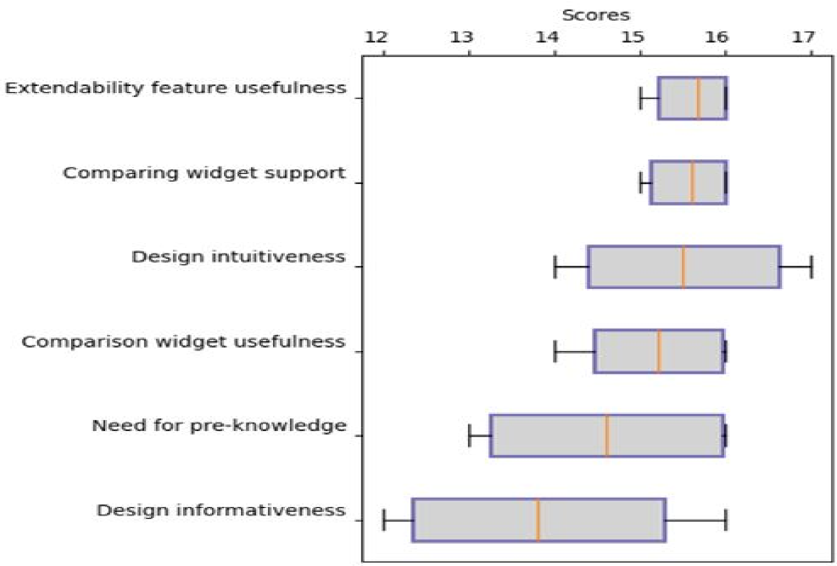

Figure 3.23: Statistical analysis of visualization experts' feedback for the functionality features of MultiCompare version (N=6)

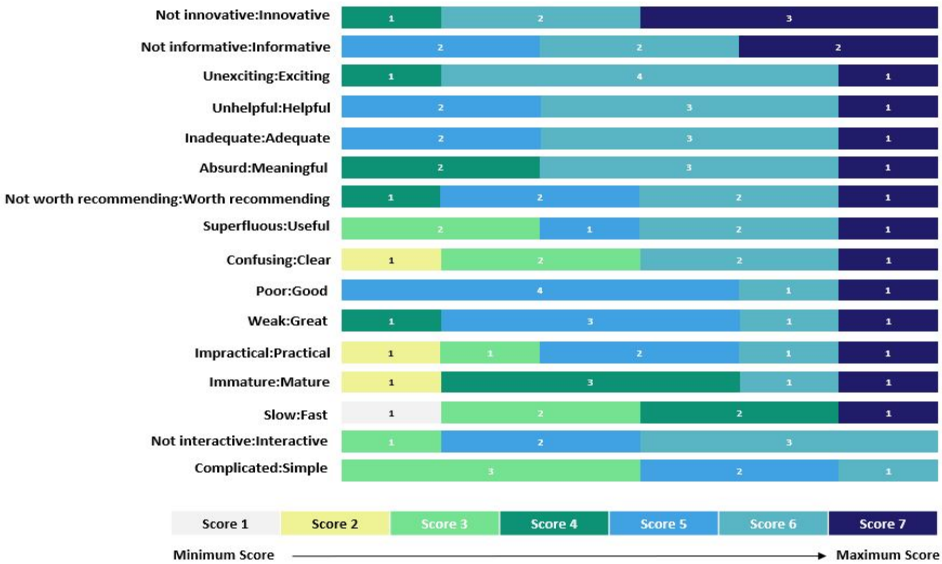

Figure 3.25: Bipolar adjective pairs (negative-positive) for MultiCompare provided by visualization experts (N=6).

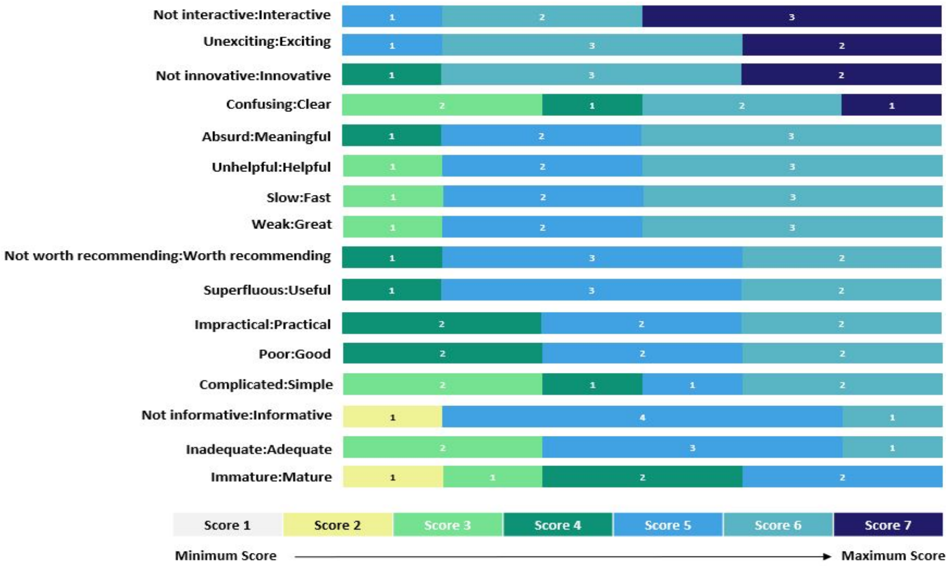

Figure 3.24: Bipolar adjective pairs (negative-positive) for BasicCompare provided by visualization experts (N=6).

3.7. Discussion

We offer a comprehensive review of the feedback and observations gathered from the studies conducted on BasicCompare and MultiCompare. This analysis primarily focuses on the aspects of comparison functionality.

3.7.1. Implications for Literature-Based with Topic-Based Discovery

Participants reported that their primary method for literature exploration was keyword-based searches in search engines (see 3.6.1). Although specialized platforms such as Neurosynth were mentioned, it became apparent that there is a clear need for more specialized functionality that facilitates the efficient comparison of relationships between brain diseases and affected regions in neuroscience literature.

The 3D brain region visualization was one of the parts of functionality that both neuroscientists and visualization expert participants find useful to understand the position of affected regions. It only needs a few improvements, such as a filter to adjust the transparency of the brain. The comparison functionality was also positively received, with the "Intersection function" identified as the most useful feature since most of the neuroscientist's tasks are about finding similarly affected regions by diseases (see Subsec 3.6.1).

Interviews with neuroscientists showed that although they are familiar with various methods for exploring and identifying relationships between brain-related topics, there is a need for functionality that visualizes the relationships between diseases and brain regions within a 3D brain model. Our functionality is perceived as valuable and useful for relationship identification and comparison tasks (see Subsec 3.6.1).

3.7.2. Usability and Explainability Concerns for both BasicCompare and MultiCompare

We received some suggestions for improvements, primarily concerning the usability and explainability of the functionality.

- Participants suggested the need for enhanced visual cues during their interaction with the features. For instance, upon selecting the Intersection function, users should receive clear visual confirmation of their selection before any alterations are made to the highlighted regions.
- They expressed a desire for more detailed information about the relationships, such as access to the underlying dataset and the number of papers mentioning the visualized relationships. These suggestions highlight the importance of refining the functionality to provide a more user-friendly experience and more comprehensive explanations of the presented topics.
- Another improvement involves distinguishing positive and negative relationships between diseases and regions in the visualization. This requires analyzing the meanings of sentences in the literature found in our repository.
- Additionally, the direction of relationships between brain topics should be considered, as sometimes a brain disease causes changes in one or more brain regions, while other times, damage in a region leads to one or more diseases. Determining the direction needs changes in relationship visualization and analysis of sentence meanings in the literature.
- Furthermore, brain visualization and the placement of spheres representing regions should be more accurate to better support neuroscientists in understanding which brain region(s) are affected by one or more diseases.

3.7.3. Differing Perspectives of Neuroscientists and Visualization Experts

The quantitative results revealed differences between the perspectives of neuroscientists and visualization experts. While neuroscientists generally found the functionality clearer, more practical, simpler, faster, more exciting, and more interactive than the traditional relationship finding, visualization experts considered it more informative and meaningful. This feedback underscores the importance of improving the functionality to meet the specific needs of its primary users — the neuroscientists.

3.7.4. Limitations

Mapping Different Names: For visualizing the brain model, we use brain region names and positions from the Scalable Brain Atlas (SBA) database. However, in the founded relationships between regions and diseases in our knowledge graph, some of the region names are different from SBA. At present, we employ a limited mapping mechanism to convert region names, but a more comprehensive conversion would require the assistance of a neuroscientist.

Finding Neuroscientists Participants: We had some challenges in finding a sufficient number of neuroscientist participants. They thought taking part in our study needed some AR/VR skills and that is why they ignored our requests.

3.8. Conclusion

In this study, we provide comparison functionality for comparing disease patterns in affected regions in an augmented reality environment. Our goal is to create a visualization that not only helps to compare disease patterns across brain regions but also improves the understanding of the multiple relationships between diseases. We provide some functionalities to identify and compare brain regions affected by brain diseases, ensuring that our visualization is both usable and explainable in terms of emphasizing similarities and differences in brain disease patterns across regions. As AR provides an immersive user interface, neuroscientists can organize topics, information, and relationships within their workspace.

In this study, we presented a visual abstraction of a 3D brain model, designed to reduce distractions. The 3D brain visualization aids in understanding established relationships and discovering new ones from the existing relationships. Furthermore, the simultaneous visualization of brain regions and their relationships with diseases helps neuroscientists find similarities in relationships, which may contribute to the development of treatment strategies.

3.8.1. Future Directions

Incorporating participant feedback to improve the functionality usability and explainability has been an important element of our development process. This involves addressing concerns such as visual feedback, color coding, and providing access to underlying literature and the topics mentioned.

The MultiCompare version of the comparison functionality has received positive feedback for its extendability, utility, and design elements, there is room for improvement in terms of reducing complexity, enhancing intuitiveness, and increasing user-friendliness. Addressing these issues will likely lead to a more satisfying user experience and wider adoption of the tool among neuroscientists.

Considering the diverse needs of neuroscientists, such as support for more brain topics (e.g., cognitive function), we need to ensure the refined functionalities have broad usability in academic research.

Conducting further studies with larger, more diverse participant samples could provide additional insights into the needed neuroscience functionalities and areas for improvement.

In conclusion, the study's findings suggest that the developed functionality has the potential to improve the comparison tasks in the neuroscience field. However, addressing the usability, explainability, and visualization concerns raised by participants will be used for optimizing the functionality for broader applications in neuroscience academic research.

4

Facilitating Neuroscience Topic-based Literature Exploration using Multiple Functionalities in Augmented Reality

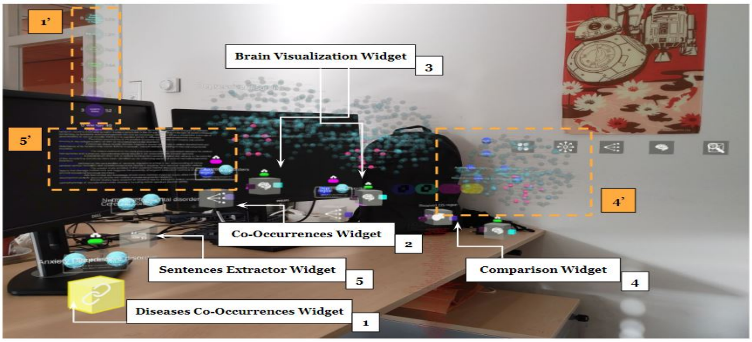

Figure 4.1: The multiple functionalities implemented for literature exploration. A user can use the "Co-occurrences Widget" (1) to identify the brain regions (1') directly related to a specific disease. The "Comparison Widget" (4) compares the regions affected by multiple diseases (4'). Two "Brain Visualizations" (3) (one for each disease) help users compare affected regions. The obtained results can be validated by the "Sentences Extractor Widget" (5) to show the publications containing the relationships (5').

An important task in neuroscience research is exploring the relationships between topics published in neuroscience literature. [5, 41] have demonstrated that an augmented reality (AR) system offering functionalities such as topic comparison, and co-occurrence discovery can support this process. We investigate how such different functionalities can be combined in a compound topic-based literature exploration task and to what extent they can together aid neuroscientists. Using a user-centered design approach, we evaluated multiple functionalities with eight neuroscientists and nine visualization experts. These specialists interacted with the multiple functionalities, utilizing them to explore relationships between neuroscience topics. The evaluation examines the usability, and efficiency of the multiple functionalities in supporting research tasks, and the overall user experience of intuitive navigation and relationship visualization. Participants' feedback validated the meaningfulness and explainability of the multiple functionalities, allowing them to gain more in-depth knowledge of complicated brain topic relationships. The results emphasize the potential of our approach in transforming neuroscience literature exploration and indicate a promising path for future study.

4.1. Introduction

Exploration of neuroscience literature is crucial for neuroscientists seeking to understand the relationships among brain regions, functions, and diseases. The huge and ever-expanding corpus of neuroscience research is both an opportunity and a challenge: while there is a lot of information available, accessing and synthesizing this material to uncover potential relationships is difficult. The use of augmented reality (AR), provides opportunities to enhance this exploration, allowing for an intuitive and explainable understanding of scientific literature. The intuitiveness of presenting these relationships in the 3D AR environment facilitates a deeper understanding of the topic relationships within neuroscience literature.

In earlier studies [5, 6, 41, 48, 49], we created and evaluated different functionalities, each supporting a specific aspect of a literature exploration task: the co-occurrence finder [5], and comparison function [50].

This study combines such functionalities to investigate more realistic, longer literature exploration and relationship-finding scenarios.

While each of these functionalities by itself is rather simple, we expect that their combination enables compounded support due to their seamless integration into the whole process.

To effectively evaluate these functionalities, we must establish tasks that support their practical use. Our first research question (RQ1) is: **What literature exploration tasks do neuroscientists use to discover relationships between brain regions and diseases, and how can multiple functionalities support these tasks?** In collaboration with three neuroscientists, we identified several compound tasks that can be used as representative tasks in our study. These compound tasks allow us to illustrate how multiple functionalities can support literature exploration and identifying relationships between neuroscience topics.

To illustrate the impact of multiple functionalities on task efficacy, it is essential to investigate their collective contribution beyond individual effects. By addressing the question (RQ2) **To what extent are the multiple functionalities meaningful at supporting the identified compound tasks?**, we ensure that the compound tasks supported by the multiple functionalities are meaningful for neuroscientists.

The explainability of the multiple functionalities is crucial for enabling neuroscientists to use them effectively in literature exploration tasks. This concern informs our third research question (RQ3): **To what extent are the multiple functionalities explainable in the context of the identified compound tasks?** We evaluate how users interact with the functionalities, focusing on their ability to understand the relationships found and how they can explain their understanding.

Lastly, the overall user experience—including data visualization, intuitive navigation, and performance—plays a crucial role in the usability of the multiple functionalities. Our fourth research question (RQ4) is **How do the multiple functionalities contribute to finding relationships between brain regions and diseases by improving the user experience in literature exploration tasks?** Through evaluating these usability features, we aim to ensure that the multiple functionalities are not only innovative but also user-friendly and effective in supporting neuroscience research.

In the following sections, we explore existing neuroscience literature analysis, the development and functionalities of AR in relationship finding, and the method employed for its evaluation. Additionally, we discuss the insights gained from this process, all aimed at demonstrating the potential of AR presentation to revolutionize how neuroscientists explore literature and find relationships between topics. We also review the range of functionalities developed so far, which we have used in this study (section 4.2).

Based on the information that we gathered from related work and talking with neuroscientists, we identify user scenarios and compound tasks to ensure the multiple functionalities can support neuroscience literature exploration tasks and relationship finding (section 4.3). We measure the meaningfulness and explainability of the multiple functionalities. This also validates their usability. We interview neuroscientists and visualization experts in in-person sessions to indicate the positive features of the provided functionalities and areas for improvement (section 4.4). We summarize the most interesting findings from our analysis (section 4.5). This synthesis not only frames the discussions and conclusions drawn from our research but also suggests future pathways for inquiry and development in this field (sections 4.6 and 4.7).

4.2. Related Work

We review individual functionalities that have proven valuable in the DatAR prototype system [6]. The goal of this review is to identify the compound tasks that can support neuroscientists in exploring literature and finding relationships between brain topics (RQ1).

4.2.1. Neuroscience Literature Exploration Functionalities

Literature exploration functionalities have been developed for exploring neuroscientific literature to find relationships between different brain topics. One of the primary goals, as stated in [6], is to provide neuroscientists with 3D presentations in AR that facilitate the process of exploring literature related to their research. Neuroscientists can discover relationship gaps and use these to help decide on experiments to conduct. Here, we categorize the functionalities into two categories; Co-occurrence finding and Comparing.

Co-occurrence Finding Functionalities

Co-occurrence refers to the instances where a topic, such as a specific brain disease, appears in the same sentence as another topic, such as a brain region. This indicates a potential relationship between these topics.

Exploring relationships between brain regions and diseases: The work in [41] introduces functionality to analyze literature using topics rather than individual publications and to present relationships across various topics. The results showed the meaningfulness of the idea behind the functionality, demonstrating that the visualization helped to better understand the relationship between brain regions and diseases.

Exploring relationships between brain topics (support more topics): Previous work supports finding relationships between brain regions and diseases. To help neuroscientists investigate the relationships between different brain topics such as protein, genes, and cognitive functions should also be considered [49]. This research used a user-centered design approach that presented both user tasks and requirements, resulting in the creation of an immersive interface designed for relationship exploration.

Co-occurrence Comparing Functionalities

The comparing functionalities provide extra support in examining how current relationships among topics can help uncover hidden or new relationships between specific topics.

Comparing relationships between diseases using affected regions: Comparison functionality was provided in chapter 3, where neuroscientists used AR visualizations to determine which specific brain regions were affected by diseases. This study demonstrated AR's effectiveness in identifying similar and different brain regions affected by different diseases. This potential of AR was further investigated in [5], which looked at its ability to improve standard literature discovery methods. The study emphasized AR's immersive aspects and its ability to produce 3D visualizations, highlighting provided functionality that uses AR's visual features to provide neuroscientific knowledge graphs, thereby assisting researchers in their relationship exploration tasks.

Comparing relationships between diseases using other brain topics: A topic model of diseases [48] was created to provide an overview of semantically similar brain diseases, indicating potential relationships. To clarify the reasons for these similarities the Brain Disease Co-occurrence Explorer (BDCE) was implemented. BDCE compares two semantically similar diseases by visualizing the number of co-occurrences between two brain diseases and other brain topics such as regions, genes, proteins, etc, mentioned in the literature. After this work, the database that the prototype originally used received a redesign. The database includes brain-related topics, such as mental processes, genes, neurons, and brain regions.

4.3. Method

This section introduces several usage scenarios that illustrate users performing compound relationship-finding tasks through literature exploration. We present several representative scenarios that illustrate the tasks we have identified as being supported by the functionalities described in section 4.2.1.

4.3.1. User-Centered Design Approach for Multiple Functionality

This section explores a user-centered design approach [36], focusing on the meaningfulness and explainability of functionalities, optimizing analysis environments for better visualization and navigation, and understanding cognitive task limitations affecting performance.

A meaningful functionality provides explanations that are understandable to the intended users [51]. Explainability aims to make the behavior of functionalities more transparent, with an emphasis on creating intuitive and clear explanations that users can easily understand and use. A significant aspect is the trade-off between the completeness of the explanation and its understandability to humans [52].

We detail how these elements are incorporated into our design and evaluation framework, aiming for intuitive, transparent, and effective user interactions.

4.3.2. Neuroscientists User Tasks

To address our **first research question, namely, "What literature exploration tasks do neuroscientists use to discover relationships between brain regions and diseases, and how can multiple functionalities support these tasks?"**, we interviewed three neuroscientists*[1] to identify tasks that could potentially benefit from multiple functionalities. In the following subsections, we provide more context and detail for each task that we used in the user scenarios. A list summarizing these user tasks can be found in table 4.1.

Table 4.1: Representative neuroscience literature exploration tasks using multiple functionalities (see sections 4.3.3, 4.3.3 and 4.3.3)

ID	User Tasks	**Source, Date**
#1	Find out which brain topics are frequently mentioned with brain disease	Cunqing Huangfu, 2019, [5]
#2	Find/explore known and unknown relations	Cunqing Huangfu, 2019, A.v. Harmelen, 2023
#3	Find robustness of the claim (e.g., relationships between a disease and a region)	K.N. Gracy, 2023
#4	Validate the shown relationships between a brain region and a brain disease	AR/VR and data visualization experts, 2023
#5	Locate related diseases in the topic model when exploring a brain topic	Cunqing Huangfu, 2019
#6	Compare two diseases in the manner of other brain-related topics	K.N. Gracy, 2022, A.v. Harmelen, 2023
#7	Look more deeply into the co-occurrence of two diseases	K.N. Gracy, 2023
#8	Find common overlaps between brain topics	K.N. Gracy, 2022/2023, A.v. Harmelen, 2023
#9	Locate related brain regions in the brain visualization when exploring a topic	K.N. Gracy, 2022, [5], 2021

[1]* K. Noelle Gracy, a neuroscientist from Elsevier Research Groups. Anna van Harmelen, a PhD Candidate from the Faculty of Behavioural and Movement Sciences Cognitive Psychology, Vrije University of Amsterdam. Felisa Van Hasselt, a neuroscientist from Elsevier Research Groups.

Task#1: Identifying Brain Topics with Frequent or Infrequent Co-occurrences in Literature

Huangfu pointed out that brain topics frequently co-occur with brain diseases in the literature, suggesting a widely accepted relationship. Topics that seldom co-occur with other diseases might present promising areas for investigation [5]. Although Huangfu specifically referred to diseases, we claim that the same principles apply to co-occurrences between different brain topics. Therefore, providing an overview that shows the most and least frequently co-occurring brain topics could be useful for users.

Task#2: Find/Explore Known and Unknown Relations & Assisting Neuroscience Researchers in Their Particular Context

Neuroscientists may require additional knowledge about a specific brain topic they are working on. For instance, a neuroscientist researching neurons might be interested in identifying related proteins, as this information could serve as a starting point for further investigations. *"The analyst must initially learn about the different topics and contents within the data and decide what to investigate first"* [53].

Task#3: Assessing the Robustness of Relationships between Topics in Neuroscience

Neuroscientists may wish to assess the strength of a relationship (e.g. between a disease and a brain region). This includes determining if the relationship is well-established or potentially a novel discovery.

Why is this important? First, knowing whether a claim is already well-supported allows scientists to build on past work. Suppose the relationship between a disease and a brain region is well established. In that case, researchers can utilize it as a starting point for their investigations, knowing that the relationship has been investigated and verified by others in the field.

If a relationship is not well-documented or is supported by only a few publications, it may indicate a novel and undiscovered area of neuroscience. Investigating these relationships could advance our understanding of the brain and diseases.

Task#4: Validate the shown relationships

The decision to provide researchers access to the source material was made following an informal brainstorming session with three data discovery experts and three AR/VR developers. The language analysis used to identify topics in a single sentence was limited. When two topics exist in the same sentence and no negating words such as "no" or "not" are present, we count a single instance of a co-occurrence. However, this approach does not verify the sentence's context or exact meaning. For example, points like "The relation between region A and disease B has been questioned." or "The relation between region A and disease B has been falsified." are both counted as evidence of a relationship in the Knowledge Graphs of Brain Science dataset. Given the possibility of uncertainty, users should be able to view the source sentences where co-occurrences are found. This will allow them to determine whether the co-occurrence contributes positively or negatively to the stated relationship.

Task#5: Identifying Relevant Diseases in the Topic Model during Brain Topic Exploration

Users can see a variety of diseases associated with a specific brain topic. This could help clarify the semantic similarities of diseases, especially when two or more diseases are close. In contrast, when two diseases are far apart, it may be useful to explore how the investigated brain topic relates to both.

Task#6: Comparing Diseases through Brain-Related Topics

The topic model gives neuroscientists an overview of which brain diseases are semantically similar and potentially related, assisting them in their efforts to discover new relationships between brain diseases. However, it does not show the specifics of direct and indirect co-occurrences, masking the relationships in the literature that lead to disease similarities. The direct and indirect co-occurrences can help comprehend the relationships between various brain diseases.

Task#7: Further Investigating Disease Co-occurrence in Neuroscience

This task focuses on understanding the interrelationships of brain diseases. The co-occurrence of two diseases, which implies they frequently appear together in papers, may imply that they share common causes or patterns in the affected brain regions. Understanding this may help neuroscience researchers to know these diseases better or find ways to treat them.

Task#8: Analysis of Shared Relationships Between Brain Topics

Examining the shared relations between brain topics may yield new insights about these relationships and the brain itself. Identifying what a group of brain topics has in common allows neuroscientists to look into their similarities while also highlighting their differences. Studying these similarities and differences might help neuroscientists better understand brain topics and offer up new areas for research, as evidenced by studies on Autistic Spectrum Disorder and Attention Deficit Hyperactivity Disorder [54]. Also, identifying new research areas can help inexperienced researchers sort through all of the relationships between brain topics and select where to focus their efforts.

Task#9: Visualization of Relevant Brain Regions

Providing a visual representation of relevant brain regions can provide an intuitive way to learn how brain topics physically correlate within the brain. As K.N. Gracy demonstrated, two brain topics could have an important relationship even if they are physically separated in the brain.

Also, neuroscientists often require help in understanding context when exploring brain topic relations, as individual brain topics can be vague and may not provide useful insights. The relevance of brain topic relations can vary based on the context of the research. For instance, a neuroscientist might be interested in understanding how a specific neurotransmitter functions in the Amygdala, with no concern for its activity in the Hippocampus. Thus, grasping the appropriate context can aid in eliminating irrelevant information and is an effective strategy for dealing with complex relationships, as noted by [55].

4.3.3. Neuroscientists User Scenarios

In this section, we design example user scenarios that correspond to the identified tasks in section 4.3.2. These scenarios are intended to utilize and integrate the multiple functionalities we have created, allowing us to analyze how well they work together in real user scenarios.

Scenario#1: Look for potentially interesting relations between Depression and brain regions to research further

- The user wants to find which brain regions co-occur with Depression (Task #1).
- The user wants to see co-occurrences of Depression and brain regions, specifically focusing on those mentioned more than ten times. This is to check that the relationships between Depression and those brain regions are sufficiently mentioned in the literature (Task #2).

  The user finds 50 relationships between Depression and the Amygdala.
- The user wants to see the distribution of publications with co-occurrences of Depression and the Amygdala and in which years publications mention these co-occurrences (Task #3 and #4)

Scenario#2: Support neuroscientists in finding missing relationships between semantically similar brain diseases

The user knows that the distance between diseases indicates their semantic similarity (see chapter 2).

- The user wants to better understand why Depression and Anxiety are semantically similar diseases (Task #5).
- The user wants to see which brain topics (e.g. genes, regions, neurons, mental process) are related to both diseases (Task #6).
- The user also wants to see how many times each brain topic co-occurs with these diseases (Task #7).

Scenario#3: Explore the regions that are affected by two semantically similar brain diseases

Continuing from the previous scenario, the user sees that some brain regions are affected by both Depression and Anxiety. The user wants to compare affected brain regions by these diseases.

- The user wants to see the location of affected regions in the 3D brain visualizations. Also, the user wants to visually compare the affected regions by two diseases (Task #8).
- The user wants to filter the affected regions to see (Task #9):

– only the same affected regions in both diseases,
– all affected regions,
– only the regions affected differently in each disease.

4.3.4. Visualization Expert User Tasks

In the previous section, 4.3.2, we detailed the user tasks employed in the study involving neuroscientists. However, these tasks do not apply to visualization experts who require a different approach, focusing specifically on the usability of visualization. So in this section, we describe the tasks for evaluation by visualization experts. Here, we do not use user scenarios because all the tasks mentioned are intended for usability testing.

Task #10: Exploring a Brain Visualization

Participants engage with an interactive brain visualization to deepen their understanding of brain regions and their relationships, particularly with Depressive disease. Initially, they use a brain visualization to identify specific regions visually. Subsequently, by manipulating the brain visualization (e.g., rotating), participants gain insights into the spatial orientation of the regions. Further exploration involves connecting the brain visualization to the co-occurrence widget to see related regions to Depressive. Participants evaluate the visualization of 3D models and the relationship and they offer feedback on how the visualization enhances their comprehension of the brain's complex relationships.

Task #11: Distinguishing Topics

Participants want to visualize a brain visualization and the disease topic model. The focus is assessing the ease or difficulty of distinguishing individual topics in these 3D models. Participants evaluate the visualization of topics. They highlight the challenges and ease of distinguishing topics within the visualizations.

Task #12: Usability of Interface and Multiple Operations

The task aims to assess the usability of the interface and the performance of multiple functionalities. Participants navigate through the user interface to interact with different widgets, including the topic model, sentence extractor, and brain visualization, to evaluate the intuitiveness of the visualization and navigation of each widget. Participants also generate, connect, and delete some of the widgets of their choice to provide feedback on the ease and speed of the widgets.

Task #13: Real-Time Changes

Participants modify the input topics of functionalities to generate new outputs, allowing for an assessment of the functionality's responsiveness. This involves a dynamic interaction where changes are made in real-time to evaluate how quickly and effectively visualizations and results update based on the new inputs. Participants evaluate the performance of the functionalities and describe their experience with the functionalities' responsiveness, highlighting any delays, efficiency, or challenges encountered during the process.

4.4. Evaluation

This section is divided into four subsections: "Customizing Feedback: Participant-Led Scenario Selection," where participants' freedom to choose their scenarios enhances the study's relevance; "Participant Engagement and Data Collection," which details the task execution and data gathering process to ensure active participant involvement; "Participants," describing the profiles of the neuroscientists and visualization experts involved in the study; and "Tasks and Procedure," outlining the session structure.

4.4.1. Customizing Feedback: Participant-Led Scenario Selection

To ensure the feedback we receive in the study is valuable, we allowed participants to select the scenario(s) that interested them. This way can obtain meaningful and engaged responses. Participants who choose specific topics are more likely to be invested in the task, improving the reliability and depth of the insights they provide. This strategy ensures that the feedback is directly relevant, which improves the study's overall effectiveness.

In the first scenario, participants were requested to choose an initial topic, which could be either a brain region or a disease. Subsequently, they can suggest a particular brain region/disease name or request an example.

4.4.2. Participants

Eight neuroscientists, PN1-PN8 including one of the three experts part of the initial interview, carried out the scenarios in light of their neuroscience research objectives. Nine visualization specialists (PV1-PV9) with experience analyzing literature but no background in neuroscience reflect on their experiences, their comprehension of the functionality of the prototype, and their observations of the visualization since they understood the literature exploration goal. All participants took part in an in-person session while wearing a HoloLens 2 headset.

4.4.3. Evaluation Procedure

Throughout the study, participants carried out various tasks. We posed questions following the tasks to ensure participants fully concentrated on every task.

Each session for neuroscientist participants, lasting around one hour, was initiated with a briefing on the method employed to explore and analyze relationships between neuroscience topics. Following this, participants were introduced to the multiple functionalities implemented in the prototype, as illustrated in Figure 4.2. Then they carried out the tasks within their selected scenarios (see sections 4.3.2 and 4.3.3). This process took roughly 20 minutes. After that, they answered interview questions about meaningfulness and explainability (see questions in appendix B.0.2).

For visualization experts, each session lasted around 30 mins. It started with a brief on the goal of the study. Then they carried out step-by-step tasks (see section 4.3.4). At the end, they were asked to fill out a survey about their feedback on visualization features (see questions in appendix B.0.4).

Figure 4.2: Designed prototype with multiple functionalities.

4.5. Results

We present feedback from all participants (8 neuroscientists and 9 visualization experts). Feedback was gathered and organized based on research questions RQ2, RQ3, and RQ4. We summarize feedback and provide suggestions for improvement.

4.5.1. Multiple Functionalities Feedback by Neuroscientists

We interpret the feedback from eight neuroscientist participants on the perceived meaningfulness and explainability of the multiple functionalities (RQ2 and RQ3). Individual and group insights are used to determine areas for improvement.

Multiple Functionalities Meaningfulness (RQ2)

This part will answer our second research question (RQ2) **To what extent are the multiple functionalities meaningful at supporting the identified compound tasks?**

Relevance to Research Activities: The multiple functionalities were valued for the ability to identify relationships between brain topics, *"I think it is very meaningful, especially because when I choose the third scenario. A lot of times it happens that I have to skim through papers and papers and papers trying to find similarities. For example, as you know, we did depression and anxiety but also when it comes to schizophrenia and bipolar. I worked on my bachelor thesis on schizophrenia, so I was looking at all of these similarities, but of course, I had to do it the old way just by using my eyes and reading and trying to find this. So I think it is very, very meaningful."*, PN7. While some participants (7 out of 8) appreciated its search engine-like functionality and found it useful for their research, one neuroscientist (PN4) felt it was irrelevant, raising concerns about its utility and efficiency. They believe the relationships between brain topics are more complex than what can be derived solely from exploring literature and presenting relationships in AR.

Topic Relationships Presentation: The multiple functionalities received high ratings for their relationship visualization capabilities, which enable researchers to find hidden or even new relationships between brain topics. Its graphical representation of highlighted or unhighlighted regions has been identified as aiding in understanding complex relationships, *"... I would focus, for example, I have seen Vermis was highlighting in depression and wasn't in anxiety, so I would focus on that areas if I want to make a strong case. ..., so I would say, yeah, if I were to make a hypothesis, I would be like, OK, what is the real difference between anxiety and depression? ..., let's investigate these areas(regions) more"*, PN7.

Insights and Hypothesis Formation: Participants appreciated the multiple functionalities to identify possible relationships and develop hypotheses, *"It can be very helpful to find it like showing the numbers (co-occurrences) and also the relation between diseases and the brain regions. ... it's based on some corpus, some data and it eases the work of scientists in a good way. They can just refer to these numbers and use this tool (multiple functionalities) to assess their hypothesis to see if their hypothesis is mentioned in the literature."*, PN6. Color coding and spatial orientation, in particular, were credited with improving the experience of understanding relationships with neuroscientists.

Future Neuroscience Research Directions: Participants believed that using the functionalities has enormous potential for assisting neuroscientists in finding new areas of investigation, PN2. The functionalities received high marks for their capacity to serve as a research starting point, especially for researchers pursuing new areas of study or for those who want to do review work, *"... when they (scientists) consider many scientific findings and they write those reviews, ... So it might take a while and they also don't cover everything necessarily like there can be gaps, and when a tool like this is used, it can almost Kind of automates part of that process. ... Quick efficient way to find links."*, PN5.

Multiple Functionalities Explainability (RQ3)

This section addresses our third research question (RQ3) **To what extent are the multiple functionalities explainable in the context of the identified compound tasks?**

User Interface Intuitiveness: The user interface was described as intuitive and user-friendly, with comparisons made to the clarity of other visualization media (PN2, PN3, PN6, PN7, PN8). This user-friendliness was perceived to allow for natural interaction (e.g. grabbing objects, rotating objects) and reduce the learning curve with the multiple functionalities, *"... since there is no external device attached to you and it is just based on your move the hand movement, I think the interaction is quite intuitive because it's similar to the interaction that you have with your smartphones ..."*, PN8.

Multiple Functionalities Experience: Users appreciated the comparison functionality for relating diseases to brain regions for its clarity and ease of use, PN2, PN3, PN7. Participants agreed that the functionality-engaging nature and clear visual results contributed to a better literature exploration.

Understanding Complexity of Relationships: The multiple functionalities that simplify complex relationships into understandable ones were positively acknowledged by neuroscientists, PN3, PN6, PN7. One participant (PN8) acknowledged the effectiveness of multiple functionalities in illustrating the affected regions in brain visualization as well as their potential to provide an intuitive way to explore relationships *"... the other one (widget) that is helping to understand the correlation in the model of the brain that is very useful, especially if you are not very familiar with the regions of the brain because people come from different backgrounds."*.

Proposed Enhancements

To improve multiple functionalities' meaningfulness and explainability, the following improvements were suggested by neuroscientists:

- Improving the research guide by including more explanation and levels for functionalities *"... I think I understand what the concept of this thing work and I just tried two or three widgets and again if I had a bit of training I would probably manage to understand better... The logic of the interface seems quite good to me, and the symbols are very clear and like it's very nice. ... I think I need more patience and more training or the thing needs to be better, Or all three."*, PN3.

- Extending the repository to include a broader range of brain topics, such as cognitive functions, would increase the utility across multiple neuroscience domains *"... if you're maybe a genetic researcher who's interested in a specific series, which is something that does happen a lot, some people kind of dedicate their whole research career to finding genes that contribute to, like Alzheimer's or something and then if you use this tool, you could really just get a list of genes that have been mentioned in, like Specific combination of disease ..."*, PN2.

Final Thoughts

Finally, the feedback stresses the multiple functionalities' role in enhancing the method of identifying relationships between brain topics. Participants recognized its strengths in relationship presentation, intuitive design, and hypothesis development help. The improvement suggestions will allow us to improve the potential for a wider domain and better impact.

4.5.2. A Comprehensive Analysis of Visualization, Navigation, and Performance Feedback by Visualization Experts (RQ4)

This part will answer our last research question (RQ4) **How do the multiple functionalities of data visualization, navigation, and performance contribute to finding relationships between brain regions and diseases, and improve the user experience in literature exploration tasks?** The result consists of responses from 9 experts to 9 questions (Q1 to Q9). Each question was rated on a scale from 1 (low score) to 10 (high score). The questions and responses are as follows, Figure 4.3:

Interpretation

The result suggests that the visualization experts generally had a positive view of the immersive model, as indicated by the high average scores. The mean score for all questions, except for "How would you rate the tool's use of color, shape, and layout in visual representations?" (Q3), is 8, indicating a generally positive response from the experts. The mean score for Q3 is slightly lower at 7, suggesting a slightly less positive view of the visualization of the topics.

The larger standard deviation for "How would you rate the quality of the visual representations provided by the tool?" (Q1), "How effective do you find the tool's visualization in illustrating complex topic relationships?" (Q2), "How would you rate the tool's use of color, shape, and layout in visual representations?" (Q3), and "How would you rate the effectiveness of the tool's navigation in helping you explore the topics and relationships?" (Q8) indicates that the scores for these questions had more variation compared to the other questions, indicating a wider range of opinions among the visualization experts for these questions.

The high maximum scores for all questions indicate that visualization aspects were highly rated by at least some of the visualization experts. However, the minimum scores for Q2 and Q3 were lower than for the other questions, indicating that there was at least one expert who held a less favorable opinion about certain visualization aspects.

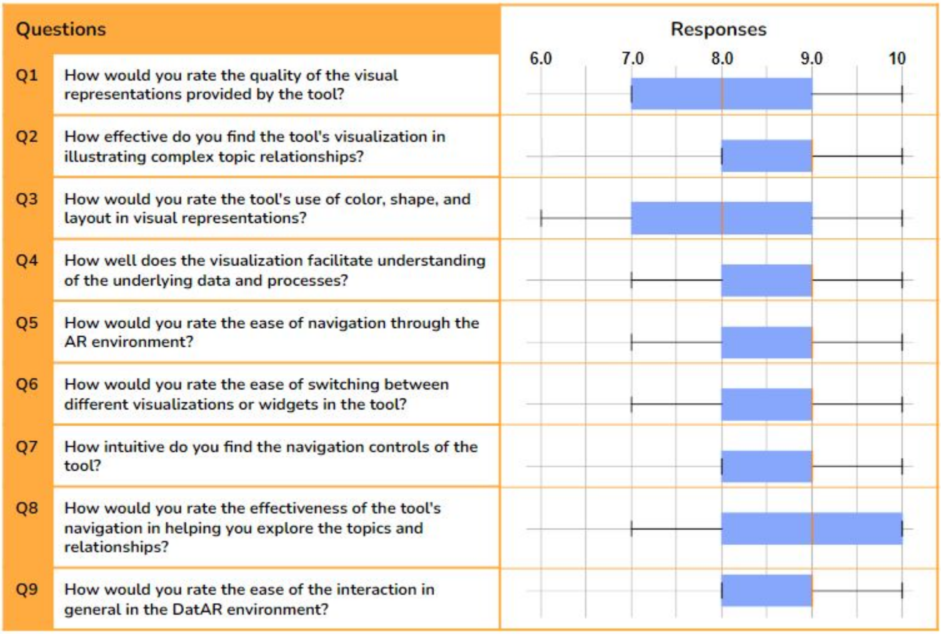

Figure 4.3: Nine visualization experts rate nine questions from 1 (low score) to 10 (high score).

Recommendations

Based on the result, it may be beneficial to further investigate the aspects of the topic visualization related to Q1, Q2, Q3, and Q8, given the greater variation in scores for these questions.

- Q1: Quality of Visual Representations - This question assesses users' perceptions of the overall quality of the visual aids provided by the functionalities. A deeper investigation here would help understand which qualities (clarity, accuracy, aesthetics) are well-received and which are lacking.
- Q2: Effectiveness in Illustrating Complex Relationships - This question evaluates the functionalities' capability to demonstrate how various topics are related.
- Q3: Use of Color, Shape, and Layout - This question looks at the specific visual elements used in the representations—color, shape, and layout. Investigating this could help in understanding the intuitive nature of the design and whether these elements are used in a way that enhances user comprehension.
- Q8: Effectiveness of the Navigation - This question addresses the navigational aspects, particularly how well it helps users explore and find relationships between topics. Solving navigation challenges is an opportunity to make the user experience more fluid and intuitive.

Understanding the reasons behind the lower scores and the variation in scores could provide valuable insights for visualization improvement, but it needs another method of evaluation that can ask users the reasons for each rate.

4.6. Discussion

Our multiple functionalities are meaningful and explainable for neuroscientists based on their feedback. These functionalities are not only usable but also transparent, trustworthy, and beneficial to users based on visualization experts' opinions.

Here, we explore the consequences of our results and suggest future development strategies.

4.6.1. Fostering Deeper Engagement and Exploration

Interactive Learning Elements: Adding interactive learning features can increase engagement and exploration, particularly for new neuroscientists. This could include a guide of the functionalities or interactive case studies demonstrating functionalities' use in representative literature exploration tasks.

Making Decision and Supporting Task: Making decisions about selecting initial brain topics to work with the multiple functionalities showed significant consideration for specific study goals. These functionalities support compound tasks, with interactive models and filters that allow neuroscientists to navigate and interact with topics.

Enhanced Data Visualization Approaches: The feedback suggests a need for more advanced object visualization approaches. For example, for presenting text in an immersive environment, we can employ techniques such as augmented reality overlays, which can dynamically interact with the user's viewpoint to enhance readability and engagement. Additionally, using 3D typography can make the text more integrated with the spatial aspects of the environment, allowing for a more natural and intuitive exploration of information. Interactive elements, such as touch-responsive animations or voice-activated commands, can further improve the user's ability to manipulate and delve deeper into the textual content.

4.6.2. Addressing Specific Concerns and Enhanced Functionality

Improve Visual Design: The significantly lower scores for visual elements (Q3 in Figure 4.3) indicate that more emphasis should be placed on the design of the topics. We can enhance the visual design by adopting a more cohesive color scheme that aligns with the cognitive load and emotional response desired by the user. Introducing uniform shapes and structured layouts can aid in better categorization and recognition of topics, thereby simplifying navigation and comprehension. Additionally, we could implement adaptive design techniques that adjust visual elements based on user interactions and preferences.

Improving Navigation and Usability: Variations in ratings for the navigation and usability (Q8 in Figure 4.3) suggest the need for a more intuitive user interface. We could implement context-sensitive help features that provide users with tips and guidance based on their current actions or challenges they appear to be facing.

4.6.3. Leveraging Feedback for Future Development

Systematic Feedback Integration: Establishing a systematic process for collecting user feedback for ongoing improvement is critical. This could include regular updates based on user feedback and suggestions to ensure the tool remains up-to-date and effective.

Expanding the Repository's Scope: Neuroscientists have suggested expanding the database to cover a broader range of topics. This expansion may include more specific information on other brain topics or upcoming research areas.

4.6.4. Functionalities Importance and Usage in Relationship finding

Our categorization of functionality importance is derived from observations made while employing them for doing the task by neuroscientists and visualization experts within this study. Note that these classifications are specific to the scenarios encountered in our research and may vary under different scenarios. Our main functionalities are The brain visualization, Topic Model, and Co-occurrence Explorer, table 4.2. By utilizing at least these functionalities, users can conduct several neuroscientists' scenarios and obtain an overview of the relationships between brain topics.

4.6.5. Collaborative Development and Community Engagement

Ongoing Research and Development of Partnerships: Our findings not only support the effectiveness of our user-centered design approach but also validate the incorporation of experts in the design process. This underlines the value of building collaborations with educational institutions and tech companies to provide vital resources and insights for future development. These collaborations could focus on strengthening the tool's technological capabilities and ensuring that it keeps up with the most recent scientific advances.

Table 4.2: Functionalities' importance based on the number of tasks they were used in.

Functionality Names	**Usage Count**	**Priority based on Count**
Brain Model Visualization	5	1
Disease Topic Model	5	1
Co-Occurrence Explorer	3	2
Sentences Extractor	2	3
Filtering the Co-Occurrences	2	3
Class Retrieval	2	3
Comparison Functionality	1	4
Brain Disease Co-occurrence Explorer	1	4

4.7. Conclusion

We investigated the use of multiple functionalities for neuroscience literature exploration. These functionalities were designed to support the understanding of relationships among brain-related topics. The functionalities were used together to support neuroscientists in compound relationship-finding tasks. Finally, this study confirms the findings of prior studies regarding the meaningfulness, explainability, and usability —focused on visualization, navigation, and performance— of the multiple functionalities. Our participants reflected on multiple functionalities' ability to support research activities, find relationships, and facilitate insights and hypothesis development.

5

Conclusion

This thesis investigates supporting neuroscientists with literature exploration and finding relationships among brain topics using Immersive Analytics (IA) visualizations. IA visualization and interaction make the implemented functionalities a valuable complement to existing literature exploration methods in neuroscience. We used the Relationship-Finding task as an initial task to explore neuroscience literature and find relationships between brain topics. In the subsequent sections, we summarize the studies we conducted (sections 5.1, 5.2, and 5.3), offer our final thoughts on the limitations encountered during these investigations, discuss possible solutions, and provide a general summary of the whole thesis (sections 5.4 and 5.5).

5.1. Usable Relationship Finding Functionalities

In this section, we explain the findings from Chapter **??**, addressing its limitations and potential future research avenues.

5.1.1. Exploration Functionality by using a Representative User Task

After discussing with a neuroscientist, we considered a relationship-finding task that asked neuroscientist participants to find relationships between a brain region and diseases (see 2.6.2).

The first version of our functionalities was introduced to eight neuroscientist participants. They understood the idea of the relationship-finding functionality and judged the 3D visualization of relationships between brain regions and diseases to be usable. Using their feedback, we improved interactivity and expanded support for additional user tasks (see 2.7). This included the ability to find relationships from a region to diseases and vice versa, as well as a sentence extractor. Experts in literature exploration evaluated this version, providing valuable insights into the visualizations of the implemented functionalities.

5.1.2. Displaying Relationships

A specific textual label represents every brain topic in our design. We used colors such as red, turquoise, and yellow for topics in the 3D models to show the type of relationships— related, unrelated, and related but outside the filter range, respectively. However, this sometimes made it hard for users to understand the depth of and the distance between topics. Also, the long names of topics were difficult to read. To consider the right color map for the different topics, we can not use the general rules that Data Visualization methods offer to us. Instead, in an AR environment, digital objects appear with different backgrounds, we have to make sure that we use colors that are visible and sufficiently distinct in any position. The color selection topic would be considered as the future direction of the research done with the DatAR prototype, (see 2.5).

5.1.3. What Users Think and Need

Neuroscientists and visualization experts found the exploration functionality meaningful and explainable. Still, users desired additional feedback mechanisms (such as auditory cues, textual responses, or tactile feedback) when they used functionalities that did not display any immediate outcomes. Another request was about supporting other topics of neuroscience research such as genes and proteins (see 2.7).

5.1.4. Identified Limitations

The brain region identifiers in the Knowledge Graphs of Brain Science (KGBS) are different in brain repositories (Scalable Brain Atlas and PubMed). To provide a scientifically reliable resource, the different terms need to be mapped to each other by neuroscience experts (see 2.9).

5.2. Compare Brain Mappings

Having established that relationship-finding between topics is a useful functionality for neuroscientists, we investigated a next step of comparing relationships found, Chapter 3. We introduced two visualization versions (Basic Comparison and Multi Comparison) since we improved the initial visualization after evaluation and reevaluated the second one.

5.2.1. Comparison Functionality by using a Representative User Task

Comparison functionality allows participants to find and compare relationships between diseases and affected brain regions. Participants of this study were asked to find information about the relationships between diseases and affected regions by comparing at least two diseases (see 3.1). Following the evaluation of this Basic Comparison functionality, we gathered feedback from visualization experts to enhance functionality, which can compare multiple diseases (MultiCompare Version).

5.2.2. Displaying Comparison

The comparison functionality offered users a filtering mechanism, allowing them to selectively explore findings within the brain visualizations. This feature, based on *"Set*

Theory,", dynamically displayed the intersections, unions, and differences between related regions for two diseases. This allowed for a more in-depth examination by clearly defining shared and separate affected regions by each disease.

5.2.3. What Users Think and Need

While participants found the comparison functionality usable and explainable, they wanted clearer feedback about the correctness of their interactions with functionalities. Also, they wanted to know more about the publications that mentioned the relationships. Furthermore, it is critical to consider the direction of relationships between diseases and brain regions to determine if a disease affected specific brain regions or if anomalies or damage within regions caused a disease (see 3.6).

Neuroscientists found the comparison functionality practical and easy to use, while visualization experts assessed it as being very informative (see 3.6).

5.2.4. Limitations and Improvements

Experts identified some limitations in our initial visualization, which have subsequently been addressed in the updated version. Initially, the usage of comparison functionality resulted in the overwriting of preliminary data within the brain visualization interface. This presented two issues: first, it prevented users from returning to the original disease-related regions, and second, the duplication of findings over two brain visualizations may generate confusion. Furthermore, in the initial version, augmented reality (AR) technology had a limited vertical field of vision, requiring a horizontal layout for object viewing. The second version's evaluation was incomplete; consequently, additional testing with a bigger participant group is required to completely determine its capabilities and address any remaining limitations.

5

5.3. Multiple Functionalities

In the final study, we combined the functionalities evaluated in the previous two chapters to assess two aspects: firstly, the collective usefulness of these functionalities in facilitating the discovery of relationships, and secondly, the extent to which the multiple functionalities retain their meaningfulness and explainability as evaluated by experts. We aimed to understand the potential of the multiple functionalities in supporting literature exploration and relationship finding while ensuring their usability and explainability for neuroscientists.

5.3.1. Multiple Functionalities to Address Traditional Research Challenges

In neuroscience, traditional exploring literature is often difficult due to the vast amount of literature available. Finding all the relationships between topics within the literature becomes difficult. Our participants validated that the multiple functionalities make this process usable, explainable, and meaningful by including functionalities for exploring literature, finding relationships, comparing relationships, and providing sources of relationships in the literature (see 4.1).

5.3.2. Participants Feedback

Our 17 participants (8 neuroscientists and 9 visualization experts) have recognized the provided functionalities' effectiveness in easily and accurately identifying important relationships in neuroscience research (see 4.5).

The intuitive user interface and functionality make relationships easier to explore and understand. However, suggestions for further improvement include additional user support, clearer explanations of widget features, and supporting more brain topics (see 4.5).

5.3.3. Impact and Future Developments

This study confirmed the multiple functionalities capabilities in presenting relationships, intuitive design, and support in hypothesis development are valuable for beginners and experienced neuroscientists.

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5.4. Limitations and Potential Solutions

We discuss identified problems and propose potential solutions based on the mentioned studies in this thesis.

5.4.1. The Recruitment of Participants

One of the most difficult challenges we encountered during our research was locating neuroscientists with specialized backgrounds in relevant fields of research. Finding participants is very time-consuming. This limitation influenced the diversity and quantity of insights we have been able to obtain. A potential solution to this challenge could be to broaden our recruitment strategies. This could include reaching out through professional networks, attending specialist conferences, and partnering with neuroscience-focused institutes.

5.4.2. Rethinking Literature Exploration

Encouraging neuroscientists to use new augmented reality (AR) technologies was a challenge. Using AR technologies presents an opportunity for neuroscientists to rethink how they explore literature. Inviting participants to immerse themselves in AR allows them to re-imagine their literature exploration process entirely. Showcasing AR's practical advantages in research through case studies or pilot projects will further encourage neuroscientists to use this innovative technology, providing a fresh perspective on their work.

5.4.3. UI Implementations — Color

In terms of technological features, the color coding used to visualize topics in the AR environment requires refinement. To improve understanding of color coding, use a palette that is universally intuitive and accommodates color vision limitations.

5.4.4. Topic Names

In terms of topic name mapping, creating a more comprehensive algorithm capable of accurately identifying differences between topic names will increase information consistency and reliability.

5.4.5. Technology Limitations

The narrow field of view provided by the HoloLens headset can detract from the immersive experience and limit functionality. Future work could investigate using other AR devices with larger fields of vision or the inclusion of software solutions that optimize information display within the limited viewing area. Continuous developments in AR technology are likely to minimize this difficulty in the future.

5.5. Last Words

We understood from participants of all studies that the IA environment has the potential to be used for serious research tasks. After conducting these studies and gathering feedback, we believe that the implemented functionalities support the initial relationship-finding task and should be completed to support more advanced ones by improving visualizations and KGBS data source support. We can use the functionalities to investigate relationships between other brain-related topics such as genes, proteins, cognitive function, and neurons. The insights provided by neuroscientists and visualization experts should be used as the foundation for subsequent phases of development and advancement.

This thesis lays the groundwork for an approach that enables neuroscientists to explore, analyze, and comprehend their neuroscience literature using immersive technologies. The multiple functionalities offer the possibility of resulting in discoveries and developments in the relationships between brain diseases, which could result in treatments for brain diseases by changing the way researchers study and understand relationships in brain-related topics (see 4.5).

Part I

Appendies

Contents

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A

addition to chapter 3

A.1. First Part

The Consent Form: `https://survey.uu.nl/jfe/form/SV_8e8U0idqMjA3kSa`

A.1.1. Topic-based discovery:

The trainer prepares the DatAR environment before using the DatAR.

- On the left there is a visualization of brain disease (Depression) and all of the regions.
- On the right there is a visualization of brain disease (Anxiety) and all of the regions.

Participants wear the HoloLens.

The trainer asks for permission to record the screen.

The trainer explains the visualizations.

Part A:

Trainer: Ask some questions

- (Usability) Is the brain visualization clear and readable to you?
- (Data interpretation) Which regions in the brain visualizations co-occur with the two diseases?
- Can you tell me something that you find interesting/meaningful in the visualizations?
- Is there anything you would like more of an explanation on in the visualizations?
- What would you like to know more about?

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  - If possible in DatAR then show participants what to do.
  - If not possible then write down the description of the new functionality

- (Data interpretation) Can you see which common parts in the brains are influenced by these two diseases?
- If you could conclude results, do you think these results are new or did you already know about them?
- If the results are not new, do you think DatAR visualization is worth using for this task?
- If you can not conclude any results, do you know what can be the reason?

Part B:

Trainer: Add a Comparing widget between two brain visualizations

Trainer: Ask the participant to wear the HoloLens again

Trainer: Explain the widget and 3 buttons (Intersection, Union, Difference)

Trainer: Ask the participant to click on one of the buttons

Trainer: Ask some questions

- Is the 3 functions that provided by buttons are understandable? If not, Trainer explains more
- (Data interpretation) Can you see which common parts of the two brains are influenced by these two diseases?
- (Usability) In comparison with the previous visualization, do you think what is the advantages/disadvantages of using this widget?
- (Usability) Between 3 buttons can you say which of them is more useful in your research field and which one is less?
- (Usability) What do you think about the provided text for each button, Do you think they are useful or useless?

A.1.2. Literature-based discovery:

The trainer asks participants to use a laptop and in 10 minutes find which parts of the brain are most affected by two brain diseases (Depression, Anxiety).

Trainer records the time that they used for searching and finding answers.

- Is the time enough for finding the results?
- If not, how long do they think they need?
- If yes, the trainer asks for the answers.

Trainer: Ask some questions

- Open question: Do you have any other feedback to give about the DatAR and this task?

A.2. Second Part

A.2.1. Post questionnaire - SUS Questionnaire

For Basic Compare

https://survey.uu.nl/jfe/form/SV_aeIUqWkgxsYE5EO

https://survey.uu.nl/jfe/preview/previewId/e63399a5-4707-4472-85f3-4e9c026865f0/SV_aeIUqWkgxsYE5EO?Q_CHL=preview&Q_SurveyVersionID=current

For Multi Compare

https://survey.uu.nl/jfe/form/SV_9Abfa0syPK7KrAi

These questionnaires are stored in the Utrecht University Survey system.

B

addition to chapter 4

B.0.1. User Scenarios (N-Version):

Scenario#1: Support neuroscientists in looking for potentially interesting relations between brain topics to research further. Neuroscientists use the DatAR tool to find new relations.

- Task#1: Identifying Brain Topics with Frequent or Infrequent Co-occurrences in Literature
- Task#4: Find/explore known and unknown relations
- Task#14: Assessing the Robustness of a Claim in Neuroscience
- Task#15: Validate the shown relationships
  - Select your desired brain region or disease to start
  - Generate the class retrieval based on the selected topic
  - Generate the co-occurrence widget
  - Generate the Topic model/brain model
  - Generate the filter
  - Connect all widgets in the correct way
  - Generate the sentence extractor widget
  - Find co-occurrences with brain diseases/regions
  - Use a filter to explore the results
  - Select a single result (disease or region)
  - Check how the information in each sentence contributes to the relation
  - Check the publication date of the documents containing the sentences

Scenario#2: Support neuroscientists in finding relations/missing relationships between semantically similar brain diseases.

- Task#5: Identifying Relevant Diseases in the Topic Model during Brain Topic Exploration
- Task#12: Comparing Diseases through Brain-Related Topics
- Task#13: Further Investigating Disease Co-occurrence in Neuroscience
  - Generate the topic model
  - Generate the disease co-occurrences widget

    The trainer gives an explanation of the distances in the topic model
  - Select two brain diseases in the topic model that are close to each other
  - Use the disease co-occurrences widget to see which topics (genes, neurons, mental processes & regions) contribute to the semantic similarity of the two diseases.

Scenario#3: Explore the regions that are affected by two semantically similar brain diseases.

- Task#13: Investigate Disease Co-occurrences
- Task#6: Analysis of Shared Relationships Between Brain Topics
- Task#9: Visualization of Relevant Brain Regions
  - Generate the topic model
  - Generate the brain models (N=2)
  - Generate the co-occurrence widget (N=2)
  - Generate the comparison Widget
  - Connect all of the widgets in the right order
  - Select two close brain diseases from the topic model
  - Find the co-occurrences between both diseases and all regions
  - Visually compare the common regions
  - Check your understanding by using the comparison widget

B.0.2. Evaluation Questions and Procedure (Version Neuroscientists - Qualitative):

Consent Form:

`https://survey.uu.nl/jfe/form/SV_5BYkcsTN9wY7e3s`

For this group of participants, we will evaluate the backend idea and the functionality of the tool in a manner of meaningfulness and explainability.

Procedure:

Begin with a brief overview of the tool's functions, the data used, and the purpose of the evaluation. Explain the concept of 'meaningfulness' in the context of this tool, emphasizing how it should enable users to derive significant insights and conclusions from the data. Explain the notion of 'explainability' in the context of this tool, emphasizing how the tool should facilitate comprehension and offer clear, understandable visualizations and outputs. A list of tasks and short definitions will be printed. The consent form will be signed by the participant.

The trainer provides the list of scenarios and the associated tasks Based on the scenario and task, the participant selects the topic of a brain region or a brain disease The trainer prepares the environment for the scenario and tasks. The participant wears the HoloLens and sees the environment. The participant runs the task with the help of the trainer (tasks' steps).

Ask the neuroscientist to explore the tool, focusing on understanding the presented data and relationships. Encourage them to think aloud, explaining their thought processes and their interpretation of the data. Encourage the neuroscientist to express any difficulties or confusion they encounter during their interaction with the tool, whether that's interpreting the visualizations, understanding the data relationships, or any other aspects of the tool's output. Ask the neuroscientist to identify specific features or data relationships that they find meaningful or insightful. This could involve exploring different disease relationships, comparing data sets, or even manipulating data parameters to create new views. Encourage the neuroscientist to express any difficulties or confusion they encounter during their interaction with the tool, whether that's interpreting the visualizations, understanding the data relationships, or any other aspects of the tool's output. The trainer asks some questions based on meaningfulness and explainability (Questions) The trainer asks her final questions

Questions:

Meaningfulness:

1. How would you evaluate the relevance of the information provided by the tool in the context of your current research activities?

2. In what ways does the tool help you make connections between different sets of data or understand relationships in the data?

3. Can you provide examples of insights gained or potential hypotheses as a result of using the tool?

4. How well do you think the tool would guide other researchers in identifying promising areas of investigation?

Explainability:

1. How intuitive is the tool's user interface?

2. Please describe the functions and outputs of the widgets you used. What is your experience with using them?

3. How effectively does the tool assist you in understanding the complexity of the relationships between different topics?

4. Can you explain the reasons behind your specific choices or decisions made while using the tool?

5. How well does the tool support the tasks you carried out? Please provide some suggestions for improvement.

Conclude the session by thanking the neuroscientist for their participation and valuable insights. Reiterate the significance of their input in refining the tool to better serve the needs of the neuroscience research community.

Final Questions:

Ask qualitative questions about the meaningfulness of the tool, such as the degree to which the data and visualizations provide valuable insights, and how the tool has helped them understand the complex relationships among neuroscience topics.

Ask qualitative questions about the explainability of the tool, such as whether the tool's outputs and visualizations were clear and comprehensible, and if there were any aspects of the tool that were particularly confusing or difficult to interpret.

B.0.3. User Tasks (Viz-Version):

Task 1: Exploring a brain model

- Step 1: Generate a brain model and identify brain regions visually represented.
- Step 2: Grab the brain model to change the view (e.g., rotate) and describe how this impacts your understanding of the position of regions.
- Step 3: Connect the brain model to a co-occurrence widget and find related regions with Depressive Disorder. Use any filtering or highlighting features to isolate specific relationships and comment on the clarity and effectiveness of the visual representation.

Task 2: Comparing Multiple 3D models

- Step 1: Generate a brain model and a topic model and use the tool to visualize them simultaneously.
- Step 2: Please describe how easy or difficult it is to distinguish individual topics in these models.

Task 3: Usability of Interface & Multiple Functionalities

- Step 1: Please point to the 1) topic model 2) sentences extractor 3) brain model widgets. Please comment on the intuitiveness of the icons.
- Step 2: Please generate 4 or 5 widgets randomly, connect widgets, and then delete them. Please let me know the ease of these operations and how long it takes to visualize.

Task 4: Real-Time Changes

- Step 1: Change the input receptacle topics in the widgets with receptacles to see new outputs. Then please describe the responsiveness of the tool.

B.0.4. Evaluation Questions and Procedure (Version Visualization Experts - Quantitative):

Consent Form:

https://survey.uu.nl/jfe/form/SV_5BYkcsTN9wY7e3s

For this group of participants, we will evaluate the visualization design of the tool in a manner of visualization, navigation, and performance.

Procedure:

Start by explaining the purpose of the evaluation and the general structure of the tool. Highlight the visualization widgets, their purpose, and how they can be manipulated. Introduce the navigation components of the tool, explaining how to navigate between different visualizations, widgets, or data sets. A list of tasks and short definitions will be printed.

The consent form will be signed by the participant.

The trainer provides the list of scenarios and the associated tasks The participant wears the HoloLens and sees the environment The participants run the task with the help of the trainer (tasks' steps) The trainer asks to fill in the questionnaire (Questions)

Questions:

The quantitative questions are stored in the Utrecht University Survey system.

https://survey.uu.nl/jfe/form/SV_c0tX3XC6zc5YvJQ

Part II

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List of scientific publications

- **G. Tanhaei**, L. Hardman, and W. Hürst, "DatAR: Comparing relationships between brain regions and diseases: An immersive AR tool for neuroscientists," in Proceedings of the 2023 ACM International Conference on Interactive Media Experiences, ser. IMX '23, Nantes, France: Association for Computing Machinery, 2023, pp. 373–375, ISBN: 9798400700286. DOI: 10.1145/3573381.3597222. Cited in Chapter 4.
- **G. Tanhaei**, "Exploring neuroscience literature and understanding relations between brain-related topics - Using Augmented Reality," in CHIIR '22: ACM SIGIR Conference on Human Information Interaction and Retrieval, Regensburg, Germany, March 14 - 18, 2022, D. Elsweiler, Ed., ACM, 2022, pp. 387–390. DOI: 10.1145/3498366.3505806.
- **G. Tanhaei**, I. Troost, L. Hardman, and W. Hürst, "Designing a topic-based literature exploration tool in AR - an exploratory study for neuroscience," in 2022 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct), Singapore, Singapore, October 17-21, 2022, IEEE, 2022, pp. 471–476. DOI: 10.1109/ISMAR-Adjunct57072.2022.00099. Forms the basis of Chapter 2.
- I. Troost, **G. Tanhaei**, L. Hardman, and W. Hürst, "Exploring relations in neuroscientific literature using augmented reality: A design study," in DIS '21: Designing Interactive Systems Conference 2021, Virtual Event, USA, 28 June, July 2, 2021, W. Ju, L. Oehlberg, S. Follmer, S. E. Fox, and S. Kuznetsov, Eds., ACM, 2021, pp. 266–274. DOI: 10.1145/3461778.3462053. Cited in Chapter 4.
- I. Troost, **G. Tanhaei**, L. Hardman, and W. Hürst, "DatAR: An immersive literature exploration environment for neuroscientists," in IEEE International Conference on Artificial Intelligence and Virtual Reality, AIVR 2020, Virtual Event, The Netherlands, December 14-18, 2020, IEEE, 2020, pp. 55–56. DOI: 10.1109/AIVR50618.2020.00020.
- **G. Tanhaei**, L. Hardman, and W. Hürst, "DatAR: Your brain, your data, on your desk - A research proposal," in 2019 IEEE International Conference on Artificial Intelligence and Virtual Reality, AIVR 2019, San Diego, CA, USA, December 9-11, 2019, IEEE, 2019, pp. 138–143. DOI: 10.1109/AIVR46125.2019.00029. Cited in Chapter 4.
- B. Xu, **G. Tanhaei**, L. Hardman, W. Hürst, "DatAR: Supporting Neuroscience Literature Exploration by Finding Relations Between Topics in Augmented Reality," in MultiMedia Modeling - 30th International Conference, MMM 2024, Amsterdam, The Netherlands, pp. 295-300. DOI: 10.1007/978-3-031-53302-0_24.

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