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BY
HOSSEIN DINI

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AALBORG UNIVERSITY
DENMARK

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Thesis submitted:	08/30/2023
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To free, brave, and inspiring women of my land, Iran…

AUTHOR CV

Hossein Dini received his bachelor's degree in electrical engineering from Zanjan University, Zanjan, Iran in 2016. His BSc focus was on the design and implementation of a novel convertor for solar panels. He received his master's degree in biomedical engineering from Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran in 2019. The focus of his MSc was on EEG functional connectivity analysis of ADHD children during a facial emotion recognition task. In 2020, he was appointed as a Ph.D. fellow at the Department of Architecture, Design, and Media Technology within a European union project called RHUMBO. Additionally, During the Ph.D. project, he has been a teaching assistant to the course Multimodal Interaction and Media Cognition and mentoring semester projects on the Medialogy and lighting design master programs while being affiliated with the Augmented Cognition Lab.

ENGLISH SUMMARY

Identification of the brain's response to various narratives and understanding the way the brain engages with narratives would lead to a better understanding of the human decision-making processes and help us to create more engaging narratives. The cognitive processes involved when humans are exposed to narratives have not been thoroughly explored using EEG metrics. Previous experiments have had significant limitations, such as conducting experiments with low ecological validity, multiple exposures to the same narrative, non-continuous narratives as stimuli, and using metrics that could not capture the continuous nature of narratives.

In this Ph.D. project, we first developed a framework in which the participants could experience a real-life continuous narrative. In this framework, contrary to previous studies that defined the narrative as an either-or concept (i.e., narrative versus non-narrative conditions), we defined "narrativity" as a scalar quality of a given artifact (video, picture, etc.). This framework would help us bridge the gap between high-level narrative concepts and low-level EEG metrics. Moreover, this Ph.D. project is the first effort to characterize different phases of the narrative dramatic arc independently.

In the second phase, we developed metrics inspired by other fields (e.g., the mental disorder field) that enabled us to explore the cognitive processes behind continuous narratives. These metrics consist of dynamic inter-subject correlation (dISC), dynamic functional connectivity (dFC), and graph theoretical features. Another issue in previous narrative studies was that they were sensitive to subjective differences. This Ph.D. project also provides robust solutions against subjective differences by developing novel features and validating them using machine learning algorithms.

This Ph.D. project consists of eight publications where we built up our framework and tested our metrics step by step. We started by testing a simple narrative concept (semantic incongruency), then developed a framework to characterize narrativity levels in parallel with developing the inter-subject correlation metric. Finally, based on the previous experience obtained from previous steps, we developed a full narrative dramatic arc trajectory in parallel with the continuous metrics.

The potential applications of this work could be used to develop new methods for evaluating the effectiveness of educational materials or to improve the design of interactive media. It could also be used to design more engaging narrative advertisements, which could be interesting for neuromarketing companies.

DANSK RESUME

Identifikationen af hjernens respons på forskellige fortællinger og forståelsen af, hvordan hjernen engagerer sig med fortællinger, vil føre til en bedre forståelse af menneskets beslutningsprocesser og hjælpe os med at skabe mere engagerende fortællinger. De kognitive processer når mennesker bliver eksponeret for fortællinger, er ikke blevet grundigt udforsket ved hjælp af EEG-metrikker. Tidligere eksperimenter har haft betydelige begrænsninger, såsom at udføre eksperimenter med lav økologisk validitet, gentagen eksponering for den samme fortælling, ikke-kontinuerlige fortællinger som stimuli og brug af metrikker, der ikke kunne fange fortællingers kontinuerlige karakter. I dette ph.d.-projekt udviklede vi først et rammeværk, hvor deltagerne kunne opleve en virkelighedsnær kontinuerlig fortælling. I dette rammeværk definerede vi, i modsætning til tidligere studier, der har defineret fortællingen som et enten-eller koncept (dvs. fortælling kontra ikke-fortælling), fortællingen som en kvalitet ved at være en fortælling. Dette rammeværk ville hjælpe os med at lukke kløften mellem overordnede fortællekoncepter og lavniveau-EEG-metrikker. Desuden er dette ph.d.-projekt det første forsøg på at karakterisere forskellige faser af fortællingens dramatiske bue uafhængigt af hinanden. I den anden fase udviklede vi metrikker inspireret af andre felter (f.eks. mental sygdomsfeltet), der gjorde det muligt for os at udforske de kognitive processer bag kontinuerlige fortællinger. Disse metrikker består af dynamisk inter-subjekt korrelation (dISC), dynamisk funktionel forbindelse (dFC) og grafteoretiske træk. En anden udfordring i tidligere fortælleundersøgelser var, at de var følsomme over for subjektive forskelle. Dette ph.d.-projekt giver også robuste løsninger mod subjektive forskelle ved at udvikle nye træk og validere dem ved hjælp af maskinlæringsalgoritmer.

Dette ph.d.-projekt består af otte publikationer, hvor vi gradvist opbyggede vores rammeværk og testede vores metrikker. Vi begyndte med at teste et simpelt fortællekoncept (semantisk inkongruens) og udviklede derefter et rammeværk til at karakterisere narrativitetsniveauer parallelt med udviklingen af inter-subjekt korrelationsmetrikken. Endelig, baseret på den tidligere erfaring fra tidligere trin, udviklede vi en fuld narrativ dramatisk bue i parallel med de kontinuerlige metrikker. De potentielle anvendelser af dette arbejde kan bruges til at udvikle nye metoder til evaluering af effektiviteten af undervisningsmaterialer eller til at forbedre designet af interaktive medier. Det kan også bruges til at designe mere engagerende narrativ reklame, hvilket kunne være interessant for neuromarketingvirksomheder.

ACKNOWLEDGEMENTS

At the age of 10, I vividly recall a day when I had a math exercise due the following morning. Returning from school, I hurried to my football club to prepare for an upcoming competition. Exhausted upon my return, I had made no progress on the exercise. It was my father who suggested we wake up at 5:00 AM to tackle it together. That morning remains etched in memory – for two hours, my father and I worked through the exercise, despite his unfamiliarity with the mathematical problem. His commitment and encouragement epitomize the lifelong support he has given me. Even during challenging times, he stood by me, guiding me through life's trials and imparting essential life lessons.

Eight years later, I faced a really big exam called Konkoor. I had to compete with a million other students for success. On that important day, I woke up to the sound of my mother praying for me before I started the four-hour test. Unfortunately, that year I didn't do well enough to get into university. I felt sad and worried about my future. My mother stayed awake with me all night, trying to make me feel better. What she did showed how kind and caring she is. It's like she taught me to be that way. If my father is like the body of this project, my mother is like its heart. Without her, these words wouldn't really have a strong meaning.

To my cherished sister, Zohre, your compassion and pure heart have been a wellspring of inspiration. Our moments of shared laughter have provided solace and hope during the most challenging times. From our earliest years, your kindness shone through, leaving an indelible mark. Your joyful approach to life serves as a beacon of positivity, adding vibrant color to the canvas of this research endeavor.

My heartfelt appreciation extends to my esteemed supervisor, Prof. Luis Emilio Bruni, whose guidance, expertise, and unwavering support have been pivotal in shaping the "narrative trajectory" of this research. I recall a day in Valencia when your hour-long conversation assuaged my frustrations. Your generosity and wholehearted support transcended the bounds of traditional supervision. Ours was a relationship that surpassed formal roles, embodying true friendship. Your insights and dedication have proven invaluable to my academic growth.

I would also like to express my gratitude to my esteemed master's supervisor, Prof. Farnaz Ghassemi. When I was new to the competitive environment of Amirkabir University, I felt completely bewildered. Your continuous support and care made a significant impact on my entire life's trajectory. I vividly remember the day when I didn't do well on an exam and you found out about it. You called me to your office, even though it was unusual for someone to fail, and you didn't blame me at all. Everything you said that day was supportive. It marked a turning point in my academic journey. I learned a great deal from you, not only about robust research methodologies but also valuable life lessons. I've observed the profound influence you've had on my current project, despite not officially being its supervisor.

To my impactful friends—Behzad Nouri, Farbod Khorraminia, Ahmad Rojuei, and Farzad Saffari—your camaraderie and unwavering support have been my refuge throughout this rigorous journey. Laughter shared and belief in me upheld have turned the arduous path into an enjoyable memory.

Last but not least, I would like to dedicate a paragraph to acknowledge and express gratitude for the presence of two remarkable individuals in my life: Faraz and Tirdad. Dear Faraz, your consistent presence throughout these years, your kindness, the love you've shown me, and the camaraderie we share have been incredibly valuable during this journey. I will always remember the day when I was under immense stress, working on finalizing a project and searching for a job. You extended your hand, assuring me that you would stand by me during tough times. The hope and confidence you instilled in me played a pivotal role in completing this project; I am deeply indebted to you.

And finally, to dear Tirdad, I find it difficult to express in words the profound impact you've had on my life. I vividly recall a day in the summer of 2018 when we sat in a park near our faculty. It was you who, with honesty and sincerity, told me that I could succeed in the academic realm. That day marked the beginning of my journey in this career, which ultimately led to the culmination of this research. Our numerous discussions about NBA, movies, and various topics are moments I always cherish and remember fondly.

In conclusion, I wish to acknowledge each individual mentioned and all others whose impact might not be explicitly noted here. Your collective support has been instrumental in achieving this milestone. As I move forward, I carry with me the lessons, memories, and connections forged during this transformative journey.

Thesis Details

Thesis Title: Towards a Characterization of Narrative Cognition: EEG metrics for continuous narrative trajectories
PhD Student: Hossein Dini
Supervisors: Associate Prof. Luis Emilio Bruni, Aalborg University

The main body of this thesis consists of the following papers:

[A] Bruni, L. E., Dini, H., & Simonetti, A. (2021, July). Narrative cognition in mixed reality systems: Towards an empirical framework. In *Virtual, Augmented and Mixed Reality: 13th International Conference, VAMR 2021, Held as Part of the 23rd HCI International Conference, HCII 2021, Virtual Event, July 24–29, 2021, Proceedings* (pp. 3-17). Cham: Springer International Publishing.

[B] Dini, H., Simonetti, A., Bigne, E., & Bruni, L. E. (2022). EEG theta and N400 responses to congruent versus incongruent brand logos. *Scientific Reports*, *12*(1), 4490.

[C] Dini, H., Simonetti, A., Bigne, E., & Bruni, L. E. (2023). Higher levels of narrativity lead to similar patterns of posterior EEG activity across individuals. *Frontiers in Human Neuroscience*, *17*, 1160981.

[D] Dini, H., Simonetti, A., & Bruni, L. E. (2023). Exploring the Neural Processes behind Narrative Engagement: An EEG Study. eneuro, 10(7).

[E] Schreiner, L., Dini, H., Pretl, H., & Bruni, L. E. (2022). Picture Classification into Different Levels of Narrativity Using Subconscious Processes and Behavioral Data: An EEG Study. In *Information Systems and Neuroscience: NeuroIS Retreat 2022* (pp. 339-348). Cham: Springer International Publishing.

[F] H. Dini, L. Schreiner, H. Pretl, C. Guger, & L.E. Bruni. Exploring Cognitive Processes in Narrative Engagement: An EEG study on interconnected attention, immersion, and memory at varying narrativity levels.

[G] Bruni, L. E., Kadastik, N., Pedersen, T. A., & Dini, H. (2022). Digital Narratives in Extended Realities. *Roadmapping Extended Reality: Fundamentals and Applications*, 35-62.

[H] Simonetti, A, Dini, H, Bruni, L. E. & Bigne, E. (2023). Conscious and Non-conscious Responses to Branded Narrative Advertising Investigating Narrativity Level and Device Type. Submitted to European journal of marketing.

In addition to the main papers, the following publications have been made during this PhD:

[1] Dini, H., Sendi, M. S., Sui, J., Fu, Z., Espinoza, R., Narr, K. L., ... & Calhoun, V. D. (2021). Dynamic functional connectivity predicts treatment response to electroconvulsive therapy in major depressive disorder. *Frontiers in Human Neuroscience*, *15*, 689488.

[2] Dini, H., Bruni, L., Ramsoy, T., Calhoun, V., & Sendi, M. S. (2022). Overlap across psychotic disorders: A functional network connectivity analysis. *Submitted to Psychiatry research Journal*, 2022-03.

[3] Sendi, M. S., Dini, H., Sui, J., Fu, Z., Qi, S., Riva-Posse, P., ... & Calhoun, V. (2021). Dynamic Functional Connectivity Predicts Treatment Response to Electroconvulsive Therapy in Major Depressive Disorder. *Biological Psychiatry*, *89*(9), S169-S170.

[4] Sendi, M. S., Dini, H., Bruni, L. E., & Calhoun, V. D. (2022, July). Default mode network dynamic functional network connectivity predicts psychotic symptom severity. In *2022 44th Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)* (pp. 247-250). IEEE.

[5] Sendi, M. S., Dini, H., Zendehrouh, E., Salat, D. H., & Calhoun, V. D. (2023). Prediction of sleep quality scores using dynamic functional network connectivity of young adults: A reproducibility analysis. *Alzheimer's & Dementia*, *19*, e065778.

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CHAPTER 1. BACKGROUND

1.1. THE RHUMBO PROJECT

RHUMBO is a European Union project funded by Marie Skłodowska–Curie Actions, which proposes investigating measures of subconscious brain processes using mixed reality technologies (MRT) and advanced biometric signal processing to improve our understanding of human decision-making. The project aims to develop tools and models to predict human decision-making in business environments. It focuses on cognitive neuroscience, transparently immersive experiences, and artificial intelligence with a specific application in consumer behavior. By leveraging MRT, biometric signals, and artificial intelligence techniques, this project seeks to examine consumer behavioral patterns in dynamic and complex situations to gain deeper insights into internal human psychological states. A total of 10 institutions (7 universities and 3 companies) contributed to this project, providing a high-level personalized multidisciplinary training program for 11 Early-Stage Researchers (ESRs). Each partner focuses on a specific aspect of consumer neuroscience. The role of Aalborg University in this project was to develop a narrative framework and evaluate it using psychophysiological signals, specifically electroencephalography (EEG) signals. Such a framework would lead AAU to investigate narrative cognitions, which would be further related to human decision-making in the context of consumer neuroscience.

1.2. NARRATIVE COGNITION

1.2.1. INTERDISCIPLINARY RELATIONS BETWEEN COGNITIVE STUDIES AND NARRATOLOGY

Postclassical studies of Narrative have taken advantage of cognitive sciences (which include various fields such as psychology and linguistics). After the post-structuralism revolution, studies under the concept of “cognitive narratology” began to rise in the last two decades(Herman, 2007). Moreover, there has been recent interest in the cognitive aspects of narrative generation (Finlayson et al., 2013; Ryan, 2006, 2015; Sanford & Emmott, 2012).

In (Ryan, 2010), the author stated that narrative is accepted as an activity that uses a cognitive mechanism to give meaning to our interpersonal relations and our temporal existence. On the other hand, it reviews the problematic aspects when considering the contribution of cognitive science to narratology and elaborates on three important domains, namely: analyzing the characters' minds, investigating the cognitive and interpretive procedures of readers and viewers, and exploring narrative as a means of conceptualizing and understanding the world. Finally, in (Y. Lee, 2012) they proposed that narrative can be considered as a cognitive tool for logical thinking, and they account for how consciousness operates considering narrative elements.

1.2.2. NARRATIVE COGNITION AND XR SYSTEMS

The current state-of-the-art in the interdisciplinary study of narrative and immersive technology consists of extending interactive narrative into mixed reality systems. Most of the contributions fell into two categories of studies. The first category is about developing narrative frameworks (Kors et al., 2016). In this category, the researchers focus on potential and limitations of developing the narrative frameworks in immersive environments, trying to overcome the limitations to provide immersive narratives. The second category of studies conducts narrative experiments in mixed/virtual reality systems (Natkin et al., 2007). This category of studies put one step further than the first category, where the implement the experiments after developing the narrative frameworks. Exposing the subjects to real-life narrative situations in mixed realties and comparing the results with the non-VR condition, they show that the immersive narratives lead to higher attention and engagement (Natkin et al., 2007). We also found studies investigating the effects of VR on user experience, VR as a narrative medium, and some elaborating on how narrative tools can be used in VR (Aylett & Louchart, 2003; Nakevska et al., 2017; Olsson & Salo, 2012; Ostrin et al., 2018).

In summary, the use of a narrative framework and its interaction with a mixed reality system leads to better delivery of narrative and its effectiveness. However, it is important to highlight that before designing a narrative framework in mixed reality, it is necessary to develop metrics and methodologies that facilitate the investigation of such narrative frameworks cognitively. In this project, the focus is on developing the metrics that further lead to designing a framework for narrative cognition.

1.2.3. DETERMINING LEVELS OF NARRATIVITY IN MEDIA ARTIFACTS

As mentioned in the literature, the level of narrativity relates to the quality of being a narrative(Oatley, 2011; Ryan, 2007). Ryan's scalar definition of narrative focuses on the degree to which objects, artworks, artifacts and other forms of representation across media possess narrative qualities (Peixinho & Araújo, 2017; Ryan, 2006, 2007). Ryan's model organizes eight steps of narrative. It has been mentioned that these steps are inclusive, meaning that being in step two implies that the narrative already has the characteristics of step one. These steps are as follows:

1) The Narrative needs to revolve around a universe inhabited by distinct entities. 2) This universe should exist within a temporal framework and experience substantial changes. 3) These changes should be triggered by uncommon physical occurrences. 4) Certain participants in these occurrences must be intelligent agents possessing inner experiences and reacting emotionally to the world's conditions. 5) Some of the occurrences must represent deliberate actions carried out by these agents. 6) The series of occurrences should create a coherent chain of cause and effect, leading to a conclusion. 7) The existence of at least a portion of these occurrences needs to be presented as factual within the narrative world. 8) The narrative should convey meaningful content to its audience. Then, Ryan categorizes these steps into four dimensions as follows: Dimension 1 includes step 1 and is called spatial dimension. Dimension 2 includes steps 1 to 3 and is called temporal dimension. Dimension 3 includes steps 1 to 5 and is called the mental dimension. Finally, dimension 4 includes steps 1 to 8 and is called the formal and pragmatic dimension. With these dimensions, Ryan seeks to liberate the definition of narrative from any singular definition, as she proposes that the question of "what is a narrative?" can be answered on an individual level, as opposed to a generalized overarching singular definition of narrative. An important thing to consider is that Ryan's model is a progressive model, in the sense that one cannot simply pick-and-choose the dimensions one finds most relevant to a definition of narrative, but instead, any inclusion of later steps per definition includes the previous steps. As a result of this function of the dimensions, each step provides a condition for elimination. For instance, she says that adding the temporal dimension would eliminate the static descriptions. Finally, Ryan's definition of narrative as a scalar property provides an elaborate concept for determining what might be regarded as levels of "narrativity".

In this PhD project, we defined a model and introduced a framework for characterizing the levels of narrativity inspired by Ryan's model (papers C, E, and F), and then investigated the cognitive process occurring behind the detection of such levels. Moreover, based on such a model we provided a paradigm by which we can split different stimuli (e.g., pictures, videos) into different levels of narrativity. In our methodology, before testing these levels with specific artifacts, we validated the pre-defined categories of the model for the level of narrativity by using online surveys, therefore capturing how the general public discriminates against these levels of narrativity, bridging the subjective aspects to our metrics.

1.2.4. RELEVANT NARRATOLOGICAL CONCEPTS – PLOT AND DRAMATIC ARC

Narratives have a natural appeal and serve as a valuable tool for comprehending emotional and cognitive processes (Sonkusare et al., 2019). Irrespective of their medium (such as pictures, text, or videos) or or their factual basis (fictional or real), narratives follow a basic structure: a beginning, middle, and end (Varotsis, 2018). Since Freytag's influential work in 1895, it has been proposed that dramatic narratives adhere to a multifaceted structure known as the narrative dramatic arc. A contemporary version of Freytag's narrative arc consists of six phases: exposition, rising action, crisis, climax, falling action, and denouement (Laurel, 1991). The exposition phase provides the background information and context for the story. During the rising action phase, the conflict is introduced, and its tension is gradually heightened. The crisis phase presents a pivotal moment where a dilemma connected to the conflict arises. In the climax phase, a decisive moment occurs, or the dilemma is resolved, often with intense action. The falling action phase shifts focus to secondary conflicts and subplots. Finally, in the denouement phase, the story reaches its conclusion.

The narrative arc's purpose is to generate and escalate tension from the story's inception until its climax, and subsequently, to gradually dissipate that tension until the Denouement (Boyd et al., 2020). Consequently, the dramatic arc furnishes a framework for crafting an engaging and immersive narrative that captures the audience's interest and sustains their involvement throughout the tale (Bilandzic et al., 2019; Busselle & Bilandzic, 2009). However, it's vital to distinguish between the author's viewpoint on the dramatic arc and its tangible impact on the audience. The alignment between the dramatic arc and the curve of engagement can serve as an indicator of its successful execution (Song et al., 2021a). Various factors can influence this alignment or lack thereof, such as poor story development or presentation, the audience's familiarity with the story or its archetypal model/genre, and more. In this context, self-reported levels of sustained engagement furnish evidence of the narrative's efficacy, thereby further informing its correlation with brain responses.

In this Ph.D. project, we selected a video excerpt that follows the dramatic arc of a narrative. We validated the presence of a dramatic arc structure within it from the perspective of the general public through an online survey. Furthermore, we captured participants' self-reported engagement ratings with the narrative and explored the cognitive processes behind the narrative's dramatic arc using EEG techniques (paper D).

1.2.5. TOWARDS AN EMPIRICAL STRATEGY

In one of our papers, we proposed an interdisciplinary theoretical and empirical framework to examine the cognitive aspects involved in processing narratives across various domains. With the increasing availability of immersive platforms and networked media, narratives are being used in education, advertising, and even for manipulation and indoctrination purposes. The objective is to identify and analyze the cognitive elements of narrative processing to understand both the beneficial and detrimental uses of narratives. By employing novel methodologies and measurement tools, we aim to characterize how people experience narratives and use this knowledge to develop effective communication strategies or counteract negative influences in digital culture.

In spite of notable progress in alternative theoretical structures and cognitive patterns over the last three decades, these breakthroughs have seldom been merged into tangible applications within the creation of representational technologies or the exploration of narrative captivation. Notably, the enactive paradigm and its variations rooted in phenomenology, which have achieved prominence in cognitive research, have not received sufficient attention in domains focused on appraising user involvement in emerging media and representational technology. (Broniatowski & Reyna, 2013). Exploring these perspectives can provide valuable insights for investigating narrative cognition and its diverse implications. We acknowledge the challenge of bridging the gap between a scientific empirical approach and the recognition of subjective phenomenological experiences. In this PhD project, we focused on identifying and characterizing the cognitive processes, features, and parameters that can be investigated using empirical methods in the interaction with narrative systems. At the same time, we kept an eye on the subjective-phenomenological aspects, validating our constructs with online surveys, interviews, and other subjective methods.

1.3. EEG METHODS FOR NARRATIVE COGNITION

In this part of the thesis, we review the analytical methods that are used to characterize narrative cognition using EEG measurements. First, we start with the Event-Related Potential (ERP) approach, which has been the most used methodology to characterize narrative cognition. We elaborate on the advantages and disadvantages of this approach. Then we dig into semantic congruency, which is an important feature in narrative cognition, and we explain how we used the ERP approach by conceptualizing the semantic congruency as an experimental paradigm. Secondly, we review the Power Spectral Density (PSD) approach that fits better to characterize continuous narratives. Third, we review the promising EEG metrics that are not necessarily used in the narrative literature but have a strong potential to uncover the cognitive processes behind narrative, and finally, we explain how we used them to characterize narrative cognition.

1.3.1. EVENT RELATED POTENTIAL (ERP) IN NARRATIVE CONTEXT

Event-related potentials (ERPs) are widely employed for evaluating cognitive processing due to their ability to provide a precise temporal analysis (Helfrich & Knight, 2019). ERPs are used in various domains such as psychiatric disorders research, food-related cognition, linguistic, and memory encoding just to mention a few (Angelovska & Roehm, 2023, 2023; Jouen et al., 2021; Silva et al., 2019; Teixeira et al., 2023). Specifically, in the context of narrative cognition, this approach has captured many studies' attention (Bruni et al., 2014; Teixeira et al., 2023; Wu et al., 2023). The most used ERP features are P300 and N400. P300 is an indication of expectancy and occurs about 300 ms after stimulus presentation. N400 is an indication of semantic incongruency, and it occurs about 400 ms after stimulus presentation. For example, Gjol et al. explored how the predictable and plausible outcomes make variations in the mental processing of individuals undergoing interactive narratives, designing a task with a combination of (un)predictable/(im)plausible events (Gjøl et al., 2018). They declared that based on N400 and P600 analysis, they saw significant differences between different conditions. Moreover, they asserted that in interactive narratives, subjects create some imagined rules to understand the narrative, and implausible events may break those rules established in the diegesis of the story world. Another study by Coderre et al. explored whether semantic processing plays a role in predicting future events in non-verbal visual narratives (the same as language processing) (Coderre et al., 2020). They found that the more predictable the narrative is, the more a decrease in N400 amplitude can be seen. Based on this and other investigations, they asserted that predictability plays a similar role in narrative processing and comprehension as in language processing. Coco et al. found a relation between plausibility and congruency, which play a role in narratives (Coco et al., 2017). They saw stronger negative shifts in incongruent and implausible settings than their congruent counterpart at 100-200 ms and 400-500 ms of ERPs.

In this PhD project, we implemented a study to investigate the semantic incongruency of brand logos (paper B). The rationale behind this study was to evaluate a simple narrative feature (incongruency) to see whether we can replicate previous results and to further develop more realistic experiments stepping on this one. The reason for choosing brand logos as stimuli was the context of the RHUMBO project. In this investigation, we delved into the brain's response to brand logos when presented alongside congruent or incongruent brand-related cues. Participants were exposed to various sets of brand-related visuals that either matched or clashed with the brand logo, while their brain activity was recorded. We extracted features related to event-related potentials and EEG time-frequency (as detailed in the subsequent section, 3.2) from the signals connected to the target image, which was the brand logo itself. The outcomes demonstrated that incongruent logos triggered a notably larger N400 peak in comparison to congruent logos, indicating a process of error monitoring. This implies that brands are deeply ingrained in consumers' minds, and the processing of logos that don't align poses a greater challenge, leading to heightened error monitoring. These findings are in line with prior research focusing on semantic inconsistencies in language and propose that the process of error monitoring extends beyond linguistic forms to encompass images and brands.

It is worth mentioning that besides the advantages of ERPs, which are ease of implementation and analysis and well-established features, there is a major limitation, which is crucial in narrative studies. Analysis of ERPs requires multiple repeated exposures of a particular type of stimuli (image or video). These multiple exposures are a deviation from the real situation because in a narrative as in real life, events are continuous and our brain recognizes them in a developmental trajectory in a specific time window, and very rarely one encounters a situation that entails the recognition of repeated single events. In summary, manipulation of experiments aiming at the analysis of ERP features would lead us to a biased investigation with lower ecological validity. Therefore, in this Ph.D. project, the main focus in the narrative context was on developing metrics that enable us to investigate continuous stimuli, rather than repeated ones.

1.3.2. POWER SPECTRAL DENSITY (PSD) OF EEG IN NARRATIVE STUDIES

Another commonly used approach in cognitive research using EEG is power spectral density (PSD). This feature translates to other features such as event-related (dis)synchronization or alpha asymmetry, based on the application. In the narrative context, several studies have evaluated various aspects of narrative such as different narrative structures, anaphoric in visual narratives, levels of narrativity, and narrative transportation (Coopmans & Cohn, 2022; Scharinger et al., 2023; Wang et al., 2016; Yoder et al., 2020). Wang et al. explored how the preference of brands and commercial products are affected by whether the advertisement includes a narrative or not, and also, how it is affected by the frequency of product exposure (Wang et al., 2016). Their results revealed that while participants are watching a narrative commercial video, they have higher theta power in the left frontal, and bilateral occipital region. Moreover, higher gamma power of the limbic system was shown while participants were watching narrative content. In addition, in bilateral temporal regions and the parietal regions, participants had significant integration-related beta and gamma power in the narrative condition. Finally, they concluded that the presence of a narrative structure in video commercials has a critical impact on the preference for branding products. In another study, Coopmans et al. examined how the order of different types of panels in visual sequences impacts the comprehension of unfolding narratives by showing short comic strips to participants (Coopmans & Cohn, 2022). They compared the brain activity while participants watched full panels vs. flawed panels. Their results showed that full panels generated increased gamma-band power compared to flawed panels. Also, the panels referred to a previous panel exhibited differences in alpha and gamma-band power compared to independent panels. They argued that the findings suggest that the processes involved in comprehending visual narratives overlap with those used in language comprehension. Yoder et al. employed a heroic martyr narrative, which emphasized personal glory and empowerment, alongside traditional social martyr narratives that focused on duty to kinship and religion using video clips (Yoder et al., 2020). The results showed that narrative transportation and the interaction between egoism and empathy predicted the appeal of the recruitment videos. Heroic videos showed increased beta power in frontal sites and globally increased alpha power. On the other hand, social narratives exhibited greater frontal theta power, indicating negative feedback and emotion regulation.

In this PhD project, we used a PSD approach to investigate the brain responses to narrative congruency vs. narrative incongruency (paper B). In the experiment mentioned in the previous section, we extracted PSD features in different EEG frequency bands alongside the ERP features. As mentioned, we investigated the cognitive processing of semantic violations between brand cues and brand logos using EEG measurements. Our findings showed that incongruence between brand cues and logos led to an increase in theta power in the mid-frontal and central electrode locations. The theta power increase in the mid-frontal area indicated difficulties in meaning integration, error monitoring, and higher working memory load. The central theta increases suggested other kinds of processes related to incongruent brand cues-logos. These results suggest that cognitive processing of brand-related stimuli involves theta oscillations and requires greater effort in integrating mismatched brand representations, reflecting higher working memory load and the detection of semantic violations.

It is worth mentioning that PSD fits better to continuous stimuli than ERP, however, it still has limitations. One limitation of this approach is due to the stationary assumption (Fell et al., 2000). EEG signals are considered as non-stationary signals therefore approaches such as PSD could not be applied to them directly, since they are based on linear models. The alternative way to use linear models for non-stationary signal analysis is to apply a window on the signals (windows from 1s to 3s). Although choosing a window is tricky, it has been well-established that the use of a windowing approach would reveal valuable information from EEG signals (Rasoulzadeh et al., 2017). Therefore, the common methodology to apply PSD on EEG signals is to apply a window on the signal, apply PSD on each window, and average the PSDs obtained from smaller windows. In the narrative context approaches like PSD limit us to evaluate a full, continuous narrative trajectory. Therefore, although the PSD approach works better than ERP for continuous narratives, they are not the focus of this Ph.D. project since we aim to analyze a full narrative trajectory. This leads us to develop and seek more novel metrics.

1.3.3. PROMISING EEG METRICS FOR CONTINUOUS NARRATIVE TRAJECTORIES

As mentioned in the above sections, the main goal of this Ph.D. project is to develop EEG metrics that are fit for the continuous nature of narrative trajectories and to further analyze the cognitive processes behind such narratives. In this part, we review promising metrics that have not necessarily been used in narrative studies but have the potential to be implemented in the narrative context. After identification of such metrics, we would elaborate on how we applied them to the narrative context.

1.3.3.1 Inter-Subject Correlation (ISC)

When individuals in a population are subjected to identical stimuli, their brains tend to display somewhat comparable reactions. The collective audience reactions encompass the engagement of sensory, perceptive, and advanced cognitive procedures. While these processes take place individually in each individual's brain, they are concurrently experienced by the entire audience as a shared phenomenon.

The utilization of inter-subject-correlation (ISC) analysis provides a means to uncover these shared responses (Schmälzle, 2022). This data-driven method assumes that there are shared brain responses to a stimulus, making the findings more applicable to a broader context. By examining the neural data of multiple individuals, this approach can identify specific brain activities that synchronize and react to a stimulus in a time-locked manner (Nastase et al., 2019). ISC is a fitting approach for the examination of functional magnetic resonance imaging (fMRI) (Redcay & Moraczewski, 2020) and electroencephalography (EEG) data (Imhof et al., 2020; Petroni et al., 2018). ISC, when applied to naturalistic stimuli, has been utilized to investigate various aspects, including episodic encoding and memory (Cohen & Parra, 2016a; Hasson et al., 2008; Simony et al., 2016; Song et al., 2021b), social interaction (Nummenmaa et al., 2012), audience preferences (Dmochowski et al., 2014), information processing (Regev et al., 2019), as well as attention, and engagement (Cohen & Parra, 2016a; Dmochowski et al., 2014; Imhof et al., 2020; Ki et al., 2016a; Poulsen et al., 2017; Song et al., 2021b).

In this paragraph, we review some studies that used ISC in a context similar to this Ph.D. project. Ki et al. explored how the ISC is related to attention engagement in a naturalistic video stimulus (Ki et al., 2016a). They designed four conditions for the experiment using audio-visual and audio-only narratives including two tasks namely normally-attend-task and count-backward-task (i.e., the inclusion of a distractor). They showed that the ISC level could be a robust index for attentional engagement levels in the naturalistic narrative stimulus. Next, when the participants were asked to count backward (while attending the narrative), their neural responses were weaker correlated across subjects than when they naturally attended to the stimuliUltimately, they stated that the level of an individual's focused involvement with real-life narrative stimuli is significantly anticipated by how closely the participant's neural reactions align with those of a broader collective. Cohen et al. investigated ways to define the circumstances under which multisensory stimulation could either aid or impede the recollection of daily encounters (Cohen & Parra, 2016a). They examined whether the crucial factor lies in the dependability of information processing (in other words ISC) while experiencing the stimulus. Moreover, they tested the memory of subjects, concerning the narrated information, three weeks later. The results showed that the performance of participants in memory questions is highly and positively related to inter-subject correlation values. In addition, they found out that while the visual stimulus alone led to no meaningful retrieval, this related stimulus improved memory when it was combined with the story, even when it was temporally incongruent with the audio. Song et al. investigated possible links between engagement fluctuations and patterns of brain coactivation and tested whether they can predict the engagement rating using brain signals (Song et al., 2021b). To this aim, participants were exposed to a naturalistic stimulus (a television episode) while continuously rating their engagement level. They declared that dynamic inter-subject correlation was able to predict the engagement ratings. Moreover, these features showed overlap with a validated neuro-marker of sustained attention and were able to predict recall of narrative events.

This approach aims to find a linear combination of electrodes, which are maximally correlated among subjects. This linear combination can be considered as brain sources (finding brain sources is similar to blind source separation methods such as ICA). They call this a linear combination of correlated components. Correlated components are similar to principal components but instead of choosing maximum variance, the maximum correlation between datasets would be chosen (Cohen & Parra, 2016b). The components would be found by solving the eigenvalue problem in the same way as PCA (Parra & Sajda, 2003). It starts with the calculation of the pooled between-subject cross-covariance, as follows:

$$R_b = \frac{1}{N(N-1)} \sum_{k=1}^{N} \sum_{l=1, l \neq k}^{N} R_{kl}$$

and the pooled within-subject covariance, as follows:

$$R_w = \frac{1}{N} \sum_{k=1}^{N} R_{kk}$$

where

$$R_{kl} = \sum_{t} (x_k(t) - \bar{x}_k)(x_l(t) - \bar{x}_l)^T$$

measures the cross-covariance of all electrodes in subject k with all electrodes in subject l. Vector $x_k(t)$ represents the scalp voltages (electrodes, for instance, 32 electrodes) measured at time t in subject k, and $\bar{x}_k$their mean value in time. The component projections that capture the largest correlation between subjects are the eigenvectors v_i of the matrix $R_w^{-1} R_b$, with the strongest eigenvalues $\lambda_i$as follows:

$$(R_w^{-1} R_b) v_i = \lambda_i v_i$$

Before computing eigenvectors, we can regularize the pooled within the subject correlation matrix to improve robustness to outliers using shrinkage (Blankertz et al., 2011), $R_w \longleftarrow (1 - \gamma) R_w + \gamma \bar{\lambda} I$, where $\bar{\lambda}$ is the mean eigenvalue of R_w. (we can select γ to be equal to 0.5).

The crucial aspect is that the within-subject and between-subject correlations, along with the resulting component vectors v_i, need to be computed independently for each experiment. This involves amalgamating data from all participants, stimuli, and scenarios. To assess the consistency of individual participants' EEG responses, it's essential to gauge how closely these responses align with the group's responses, following the projection of data onto the component vectors v_i. The ISC is then quantified by calculating the correlation coefficient of these projections, done individually for every instance of stimulus presentation and each component. This is subsequently averaged across all conceivable pairs of participants involving a particular individual. Consequently, for each stimulus, scenario, and participant k, a measure of reliability can be derived through ISC summation over components in the subsequent manner:

$$ISC_k = \sum_{i=1}^{N} r_{ki}$$

where

$$r_{ki} = \frac{1}{N(N-1)} \sum_{l=1, l \neq k}^{N} \frac{\sum_t y_{ik}(t) y_{il}(t)}{\sqrt{\sum_t y_{ik}^2(t)} \sqrt{\sum_t y_{il}^2(t)}}$$

are the conventional Pearson correlation coefficients, here averaged across pairs of subjects and computed for component projections, $y_{ik}(t) = v_i^t(x_{ik}(t) - x_k)$.

1.3.3.2 Dynamic Functional Connectivity (dFC)

Recently, the evaluation of alterations in the statistical interdependence among various brain areas (so-called static functional connectivity (sFC)) has proven to be beneficial in anticipating alterations in participants' cognitive and attentional states during task performance(Dini et al., 2020; Mohammad S E Sendi, Pearlson, et al., 2021; Song et al., 2021b). Moreover, it has been widely used in unveiling the fundamental brain connectivity patterns associated with mental disorders (Liu et al., 2020; Luo et al., 2021; Mulders et al., 2015; Yan et al., 2021). We mentioned the studies related to mental disorders since the approaches used in that area are promising to be implemented in a narrative context. Since the investigation of connectivity is argued to rely heavily on the computation of dynamic signal interactions over time (Sakkalis, 2011), it's preferable to utilize a measurement method with superior temporal resolution, such as EEG recording. There are various ways to calculate sFC such as Fisher's z-transformed Pearson's correlation (Song et al., 2021b), Phase locking value (Aydore et al., 2013), event-related phase coherence (Dini et al., 2020), etc. Researchers use any of the abovementioned approaches based on the research question, methodological assumption, and other factors. We would not mention the details of those approaches for the sake of conciseness.

Previous studies primarily focused on static functional network connectivity, which represents average brain connectivity over a complete recording. Nonetheless, this strategy fails to account for the innate dynamic character of brain functional connectivity (FC). To overcome this constraint, the concept of dynamic functional connectivity (dFC) emerged, aiming to capture the varying strength of connectivity throughout distinct segments of the time sequence. Studies have demonstrated that dFC exhibits heightened sensitivity in uncovering connectivity patterns in psychological disorders (like schizophrenia, major depressive disorder, and Alzheimer's disease) (Chen et al., 2021; Gu et al., 2020; Mohammad S E Sendi et al., 2022; Mohammad S E Sendi, Dini, et al., 2021; Mohammad S E Sendi, Zendehrouh, et al., 2021; Mohammad Sadegh Eslampanah Sendi et al., 2021; Zhu et al., 2022). Inspired by the area of evaluating mental disorders, in this Ph.D. project, we focused on dFC rather than FC.

To compute dFC, the common approach is to employ a tapered window with sufficient samples achieved through convolving a Gaussian function (Sigma = 3) with a rectangular window. Typically, the window dimensions are determined using insights from prior research, indicating that the ideal window size for dynamic connectivity analysis falls within the range of 0.05 to 0.07 times the sampling rate. (Dini et al., 2020, 2021; Mohammad S E Sendi, Dini, et al., 2021; Mohammad S E Sendi, Pearlson, et al., 2021). Then, the defined window is slid over the entire signal to cover the whole sample. Within each window, one of the abovementioned approaches is used to calculate the connectivity across electrodes, encompassing all periods and channels for an individual subject. After the calculation of the dFC, there are three ways of dealing with it. The first one is to directly use the features for the statistic/machine learning analysis. The second one is to extract the latent features out of them, and then apply the statistics. The third one is to extract graph features out of dFC (see the next section). In this Ph.D. project, we directly fed the dFC features to a support vector regressor (paper D), similar to a method used in (Song et al., 2021b). Since the approach of directly using the dFC features will be mentioned in paper D, here we will elaborate on the possible latent features from dFC, inspired by the mental disorder area, that have great potential to be used in the narrative field.

To calculate the latent features, the common approach after dFC calculation is the following steps (see (Dini et al., 2021; Mohammad S E Sendi, Pearlson, et al., 2021), which explains the steps with more elaboration). In step 1, the resulting features out of dFNC are concatenated for each subject, and the dFCs of all subjects are concatenated together, showing the changes in brain connectivity over time. Step 2 utilizes K-means clustering to group the dFCNs into different clusters, determined by the elbow criterion to find the optimal number of clusters. This results in distinct states for the participants. In addition, the output of the clustering method includes a state vector, which indicates that any of the dFC windows belongs to each of the identified states. In Step 3, features such as occupancy rate (OCR) and traveled distance are computed based on the state vector and dFCN. OCR represents the time interval spent in each state, while traveled distance measures the overall distance covered, irrespective of the state. It is worth mentioning that many other latent features can be extracted out of state vector and dFC, in addition to OCR and traveled distance.

1.3.3.3 Graph Theoretical Features

The third perspective we can take after the dFNC calculation is graph theoretical features. A functional brain graph can be referred to as an organized assembly of N nodes and L links that illustrate the neuro-dynamic exchanges amid brain regions. These exchanges are established according to the functional connectivity (FC) measurements, corresponding to specific instances of dFC. Given that FC values are continuous, the network is deemed as having weights. Consequently, a functional brain network is portrayed through its connectivity matrices, wherein nodes are aligned along rows and columns, and the matrix's elements symbolize the connections interlinking them. (García-Prieto et al., 2017). Here we describe some of the important graph features (i.e., strength (S), clustering coefficient (C), shortest path length (L), and betweenness centrality (B)). Since inspired by their use in the mental disorder field, in this Ph. D. project we used some of them in a narrative context.

1) Strength in a functional brain network refers to the connections between nodes, represented by weights. The number of links in the network can be measured as the sum of the binary weights or the sum of the weighted values. The strength of each node is computed by adding up its connections, whether in the form of binary interactions or weighted interactions. The overall strength of the network is the average strength of all its nodes. The average network strength can also function as a gauge of network density, and it can be utilized alongside network degree to evaluate diverse network attributes and their influence on the distribution of degrees and strengths. (García-Prieto et al., 2017).
2) The clustering coefficient of a network provides insight into how the network segregates information, indicating subnetwork specialization. It is calculated as the average of individual node clustering coefficients in the network. Each node's clustering coefficient represents its local clustering, taking into account the degree of the node and the number of triangles formed around it. The triangles represent the relationships between a node's neighbors, showing the probability of these neighbors being linked. The clustering coefficient portrays the inclination of elements within the network to create nearby clusters and is intricately connected to the network's resilience and ability to handle errors. Grasping the existence and configuration of triangles aids in understanding the establishment of distinct subnetworks among adjacent nodes. (García-Prieto et al., 2017).
3) The shortest path length is a measure used to assess how easily information can spread throughout a network, indicating its robustness and error tolerance. It is defined as the average shortest path length in the network, representing the average distance between nodes. By considering the global average of this metric, we can evaluate how well the network integrates information using the index L. L measures the average distance between a node and all other nodes, providing a measure of network integration. On the other hand, the clustering coefficient C captures the local clustering and neighborhood connectivity within the network. These indices, L and C, allow for the quantification of the structural properties of a graph. They provide insights into the global and local characteristics of the network, such as small-worldness, efficiency, and randomness, which help characterize the network's functionality and properties (García-Prieto et al., 2017).
4) Betweenness centrality is a metric that gauges the degree to which a node resides on the quickest routes connecting different nodes within a network. Nodes with elevated betweenness centrality are situated along numerous such swift routes. This measure can be determined by summing the

proportion of shortest pathways that traverse a specific node, relative to the complete count of shortest pathways in the network.A high betweenness centrality indicates that a node has a significant influence in connecting other nodes and can reach them efficiently. This measure highlights the importance of a node in facilitating communication and information flow within the network.

1.3.3.4 Applying these promising metrics to narrative cognition

As mentioned in sections 3.1 and 3.2, in a narrative context, we are looking for features that have two main characteristics. First, they should be fit to continuous stimuli, and second, they should be robust against subjective differences. Taking advantage of metrics such as ISC and dFC we can analyze signals collected in a continuous manner bringing three advantages to the picture. First, we can see how perception evolves through time and how the brain reacts during a narrative. Secondly, there is no need to window the signal and average across the stimuli (the procedure of ERP analysis) and lose information because of averaging. Third, these methods consider subjective differences (which could have a great impact on the results obtained). In this section, we explain how we adjusted the abovementioned metrics to fit the narrative context. ISC and dFC have been used in some narrative cognition studies to a lower extent, but to the best of our knowledge graph features have not been used in the context of narrative.

Inter-subject correlation is one of the most robust methods that considers the brain activity among the subjects (not within the subject) and is considered the reliability of an individual's neural responses concerning a larger group. Therefore, it is not sensitive to subjective differences. According to (Ki et al., 2016b), researchers have found that for a consistent evoked response to be obtained among participants or trials, each participant or trial must produce a dependable response. This reliability is analogous to conventional techniques that gauge the consistency of a response by measuring the amplification of neural activity. However, the key distinction lies in the fact that instead of presenting stimuli multiple times to a single participant, we can measure reliability across multiple participants. This approach also lends itself well to using continuous naturalistic stimuli e.g., video advertisements. Previous studies have explored the connection between ISC and narrative engagement or attention (Cohen & Parra, 2016a; Dmochowski et al., 2014; Ki et al., 2016a; Poulsen et al., 2017; Regev et al., 2019; Schmälzle, 2022; Song et al., 2021b). However, these studies often assumed that narratives can be categorized as either having narrative qualities or lacking them entirely. They considered cohesive narratives as true narratives while disregarding narratives that were meaningless or scrambled. However, from a narratological perspective, there is a growing interest in viewing narrativity as a spectrum rather than a binary characteristic. Artifacts such as pictures, videos, and stories can possess varying degrees of narrativity. In other words, narratives can exist in different degrees rather than being simply present or absent. This raises the question of how different levels of narrativity impact narrative engagement. The way we adjusted ISC to narrative context was to consider all the abovementioned narrative factors and explore how varying levels of narrativity, or varying levels of narrative engagement result in different levels of ISC, and whether ISC values can be used to predict the phases of a narrative dramatic arc (see paper D).

In addition, we put a step forward to relate the ISC to different EEG frequency bands. This gave us a strong tool to relate the ISC to well-established cognitive processes (For example attention and memory, which have been argued to be related to alpha and theta frequency bands). Drawing inspiration from (Maffei, 2020), we computed the frequency information of ISC having the same idea of ISC, but instead of calculating between subject correlation, we calculated between subject power spectrum density as below:

$$\boldsymbol{ISC_{i_{AB}}(f) = \frac{|G_{i_A i_B}(f)\ |^2}{G_{i_A i_A}(f) G_{i_B i_B}(f)}}$$

Where A and B refer to subject A and subject B, i refers to the ith channel, $G_{i_A i_B}(f)$ refers to the cross-spectral density in channel I of two subjects, and $G_{i_A i_A}(f)$ and $G_{i_B i_B}(f)$ represent the auto-spectral density of channel I of subject A and subject B, respectively.

In summary, we applied modifications to the ways we look at narratives and adjusted the ISC metric to fit such narratives, as well as correlating the ISC to specific frequency bands. This became a strong tool against subjective differences and is well-fitted to continuous stimuli.

We utilized dFC and graph features to examine the cognitive processes involved in a continuous narrative dramatic arc. To do this, we analyzed the dFC across the electrodes of participants while they watched a narrative unfold. By sliding a window across the entire signal and obtaining the FC of each window, we obtained dFC features. These features were then directly fed into a support vector regressor to identify the moments where they could effectively predict narrative engagement. By examining the characteristics of the predictor FCs, we could understand the cognitive processes underlying different phases of the narrative, such as exposition or climax. For example, we found that inter-central connectivities and the connection between other brain regions and with central region play a vital role in predicting narrative engagement using dFC. More detailed information can be found in paper D. This approach allowed us to directly utilize the dFC features. Additionally, as mentioned in section 3.3.2, there is an alternative method of extracting latent features from dFC, inspired from the mental disorders field. Although we did not discover a significant relationship between these latent features and narrative engagement, they hold great potential for narrative studies. The reason for this is that they are suitable for investigating continuous narrative trajectories (as they are based on dFC) and are particularly robust against subjective differences. This is because these features are extracted from the combined dFC of all participants, followed by a clustering algorithm applied to the combined dFC data.

Recent advancements in the field of graph theory have enabled researchers to describe the topological attributes of brain networks (García-Prieto et al., 2017). The graph features serve great potential in uncovering the dynamic of brain networks during a narrative experience. The node degree can be an indication of strength distribution over the brain regions, and the clustering coefficient uncovers the formation of subnetworks among neighboring regions. In addition, the combination of clustering coefficient and shortest path length could give us an indication of small worldness, which shows us whether the observed pattern goes towards random or towards a meaningful pattern. Finally, the betweenness centrality indicates the facilitation of communication and information flow within the network. In this Ph.D. project, we used the node degree, the clustering coefficient, and the betweenness centrality features to investigate the brain network characteristics of participants while exposed to a narrative dramatic arc. Our results indicated that the betweenness centrality score could significantly predict narrative engagement. This means that in the highly engaging moments of narrative, the information flow across the brain networks is easier than the other moments. I addition, this feature could significantly predict the "falling" and "denouement" phases of the narrative arc, which could be an indication of perspective-taking and shared understanding of a narrative trajectory (for more details see the paper D).

Finally, we evaluated the significance of the extracted features using statistical analysis and machine learning algorithms. Aligned with the design of each study, we applied a proper statistical analysis of the extracted features to see whether different conditions of the experiment differ significantly. The statistical approaches consisted of Two-way ANOVA, linear mixed models, and permutation tests, according to each experiment. Moreover, we developed machine learning algorithms to evaluate whether we can classify different levels of narrativity or predict narrative engagement. The algorithms used in this Ph. D. project consist of two main approaches. a) The first one is a support vector machine to classify the high vs. low level of narrativity (paper C) and to classify four levels of narrativity including abstract, low, medium, and high level of narrativity (paper F). Briefly, in this method, we train the classifier based on only EEG data of one level of narrativity and then test it on a leaved-out subject to explore whether the leaved-out data refers to which narrativity level. By this, we were able to significantly identify to which level of narrativity the subject was exposed, solely based on the EEG data. b) the second approach we used was a continuous support vector regressor (SVR) that we used in paper D. In this approach we calculate the correlation between continuous EEG data and continuous engagement ratings using the SVR. Then we shuffle the engagement scores 1000 times and repeat the process of correlation calculation to build up the null distribution. Finally, we test the real correlation value against the null distribution to explore the significance of the existing correlation. The main advantage of applying the abovementioned machine learning algorithms, compared to classical statistical analysis, is that we can overcome the subjective differences by training the model based on the data of all participants except the left-out participant.

CHAPTER 2. SUMMARY OF RESEARCH FOCUS

This PhD project focuses on three main areas, which makes it different than previous studies. The aim was to develop a continuous narrative trajectory as well as the features that enable us to characterize the cognitive processes behind such narrative, considering the subjective differences. Below, we elaborate on these three domains:

a) Developing a continuous, real-world narrative framework

In the context of narrative, it is a crucial point to have as much as possible a real-world experimental criterion. Previous approaches collect their data in limited laboratory situations rather in than real scenarios that provide low ecological validity. Designing ERP studies and showing images or interrupted videos are examples of such approaches. This has a significant impact on the participant's brain (or body) responses, which leads us to a biased understanding of human behavior in the given situation. Although in this project we implemented similar ERP or interrupted narrative studies (paper B) intending to develop metrics as first steps, the final target was to use a continuous narrative trajectory including a specific plot (paper D). The defined framework in this Ph.D. project (papers A and G) is more ecologically valid than showing a picture or interrupted narrative. In addition, this would be a steppingstone for designing a narrative in mixed reality systems (paper A).

b) Defining non-ERP metrics to characterize such continuous narrative trajectories:

To find cognitive faculties that play a role in narrative cognition, previous studies mainly focused on Even-Related Potentials (ERPs) or on comparing brain activity between narrative with non-narrative situations. However, analysis of ERPs requires multiple repeated exposures of a particular type of stimuli (image or video). These multiple exposures are a deviation from the real situation because in real life narrative events are continuous and our brain recognizes them in a developmental trajectory in a specific time window, and very rarely does one encounter a situation that entails the recognition of repeated single events. Therefore, in our case study, manipulation of experiments aiming at the analysis of ERP features (e.g. P300) would lead us again to a biased investigation with lower ecological validity. On the other hand, the aim of this study is not a comparison of narrative versus non-narrative stimuli. Rather, we aim to explore how cognitive processes develop during a narrative trajectory (considering the temporal development). In this study, we aim to use non-ERP features to evaluate human behavior in a simulated real narrative situation in continuous time, where the brain is unfolding its cognitive faculties to understand the situation.

c) To consider subjective differences:

A major limitation of the narrative studies is that the participants get the narrative in various ways. This leads to various brain activations +(different patterns of brain activity) while participants are exposed to the same stimuli. Therefore, analysis of the brain activity in a single subject level would lead to a biased interpretation. To address this limitation, we aim to define metrics that are robust against such subjective differences and analyze brain activity at a global level.

CHAPTER 3. SUMMARY OF PAPERS

The main contribution of this Ph.D. thesis consists of eight publications presented in chapter 6. The goal of these publications was either to make a stepping stone or directly address the main focuses of this project, provided in the previous section. In this chapter, we provide a summary of the motivation, methods, and findings of the listed publications. In papers A and G, we introduced a framework for narrative cognition, and reviewed previous literature on narrative, introducing a new way of exploring narrative cognition which would be further used in mixed reality systems. In paper B, we examined a simple narrative feature, semantic congruency, using a well-established ERP and time-frequency features. The aim was to reproduce the previous narrative finding in the context of the RHUMBO project and also set up the equipment that we used in further studies. In papers C, E, and F, we explored cognitive processes behind different levels of narrativity (two levels in paper C and four levels in papers E and F). we used and adjusted the ISC metric in these studies. These two studies are a step towards a continuous narrative trajectory, where we validated our framework and tested our defined metrics. Paper D is the main paper of this Ph.D. project where we used all the experiences we have gathered throughout the Ph.D., defining a continuous narrative trajectory, testing the narrative dramatic arc plot, exploring the continuous narrative engagement, and using novel metrics to characterize the cognitive processes behind it. Finally, the paper H indicates the application of narrative cognitions in the context of RHUMBO project, consumer neuroscience.

Paper A: Narrative cognition in mixed reality systems: Towards an empirical framework

The intention of this paper was to create a conceptual structure for the notion of narrative cognition within mixed reality systems, with the goal of bridging the divide between empirical scientific methods and the personal experiential aspect connected with narratives. We stress the necessity for further study and theory to recognize and describe the cognitive mechanisms, characteristics, and factors entailed in engaging with narrative systems. Moreover, we underline the absence of incorporation of different theoretical frameworks and cognitive models into practical applications for the advancement of representational technologies and the analysis of engagement with narratives. Additionally, we address concerns about the tendency of experimental approaches to narrative cognition concentrating on automated and unconscious mental procedures, which may already be familiar to literary scholars and narratology experts. We contend that the focus should be on illuminating vital elements of narratives and examining more advanced cognitive processes sparked by narratives. Our proposition introduces an interdisciplinary framework aimed at harmonizing cognitive and psychological viewpoints on narrative cognition, with the objective of comprehending the cognitive mechanisms linked to interactions with narrative systems. Finally, we acknowledge the potential of mixed reality systems and technology in providing insights into narrative cognition and its implications.

Paper B: EEG theta and N400 responses to congruent versus incongruent brand logos

The primary motivation for the first paper was to investigate one of the established narrative features, semantic congruency, to evaluate whether we can replicate the previous findings in the literature using the combination of EEG and VR headsets in the context of the RHUMBO project. To this aim, we designed an experiment to explore the neural and behavioral responses to congruent and incongruent brand logos using EEG theta-frequency and N400 features. The study involved 30 participants who were shown a series of brand logos followed by either congruent or incongruent pictorial brand-related cues. The results, in line with the previous studies, showed that incongruent brand logos elicited a larger N400 response than congruent brand logos, indicating that mismatched brand logos require more cognitive effort and result in greater error monitoring. The theta power was also found to be higher in the incongruent condition, suggesting that incongruent brand logos require more cognitive resources. The findings of this study contribute to the understanding of the meaning of brands and the semantic processing involved, indicating the deep encoding of brands in consumers' minds. These findings shed light on the semantic processing of brands and emphasize the significance of congruence in brand logo design and marketing strategies. It is worth noting that this paper was ranked among the top 20 impactful papers in the neuromarketing field awarded by the Neuromarketing Science & Business Association (NmSBa).

Paper C: Higher levels of narrativity lead to similar patterns of posterior EEG activity across individuals.

The motivation for implementing this study was to delve into the relationship between narrativity and brain activity, aiming to unravel the cognitive mechanisms involved in different levels of narrativity (high vs. low level). In this study, we investigated how higher levels of narrativity influence posterior EEG activity across individuals. To conduct the study, we first chose and assigned 12 narrative video advertisements to two levels of narrativity (6 videos per category), and then we validated our narrativity level with 150 participants watching and scoring the videos. Then the participants were exposed to narratives with high or low levels of narrativity in a random order. The participants' brain activity was measured using EEG, specifically focusing on posterior brain regions. Additionally, self-reported data on engagement levels were collected. The findings propose that individuals might demonstrate increased responsiveness to mutual perspective-taking, implying a collective grasp of the narrative, instead of their levels of involvement. Furthermore, narratives characterized by elevated levels of narrativity were observed to prompt comparable interpretations among the audience when contrasted with narratives possessing lower narrativity levels. This highlights the significance of narrativity in shaping audience understanding and interpretation. We argue that understanding the cognitive processes involved in storytelling can provide valuable insights into how narratives are processed and comprehended by individuals. This research contributes to the comprehension of how viewers process and comprehend communication artifacts, focusing on the narrative attributes delineated by the degree of narrativity.. The findings contribute to the fields of neuroscience and psychology by advancing our understanding of how narratives are processed and understood by individuals.

Paper D: Exploring the Neural Processes behind Narrative Engagement: An EEG Study.

Implementing previous studies on the scalar model of narrativity where we investigated neural processes behind levels of narrativity, we implement this study to evaluate the cognitive processes behind a full, continuous narrative trajectory. Previous studies have focused on cognitive processes using naturalistic stimuli but have not specifically examined the narrative structure itself. In this study, we aim to use those metrics that we have defined in our pipeline based on our previous studies to investigate a full narrative structure and its phases and their relation to engagement. This study involved presenting participants with an excerpt that possessed a narrative dramatic arc structure. We analyzed the EEG data using various metrics, including dISC (dynamic inter-subject correlation), FC (functional connectivity), and a graph theoretical feature, BC (betweenness centrality). These metrics provided insights into the neural correlates of engagement and the predictive power of different brain regions. The results indicated that the moments generating the highest engagement ratings within the excerpt corresponded to the climax phase, while less captivating instances aligned with other phases. This implies that the narrative adhered to the expected pattern of a dramatic arc. Moreover, the EEG data analysis revealed that FC5 displayed the greatest coherence among the three notably correlated channels, with two of these channels concentrated in the frontal-central area of the left hemisphere. This finding suggests a pivotal role of the left hemisphere's frontal lobe in processing narrative engagement. Additionally, we explored whether alterations in group-averaged engagement ratings could be predicted through pre-processed EEG amplitudes. Our findings underscore the complementary nature of the three metrics employed in the study: dISC, FC, and BC. Together, these metrics collectively furnish a comprehensive evaluation of narrative cognition with a focus on levels of engagement. While dISC effectively anticipated narrative phases prompting heightened engagement and lower shared understanding, FC and BC successfully predicted stages prompting reduced engagement and heightened shared understanding. This indicates that distinct brain regions and connectivity patterns contribute to various facets of narrative engagement. This paper argues that investigating variations in brain responses between linear and non-linear narratives could pave the way for exploring cognitive processes in interactive and immersive narratives.

Paper E: Picture Classification into Different Levels of Narrativity Using Subconscious Processes and Behavioral Data: An EEG Study.

In this paper, we evaluated the effect of the four different narrativity levels on human brain response. A total of 27 participants were exposed to a total of 40 paintings from abstract, low, medium, and high levels of narrativity (10 paintings per category). After seeing each painting for 15 seconds, the participants responded to self-reported questions measuring the narrative engagement. Following that, the paintings from each category were put in a pool of target and non-target stimuli and were shown to participants for one second to collect EP responses. We a comprehensive investigation using evoked potentials (EPs) and behavioral scales to assess the narrativity of paintings. The preliminary findings of the study shed light on the impact of seen images on EPs compared to unseen images, particularly in pictures with abstract and dramatic (high-level) narratives. One significant discovery of the study is the identification of the N600 potential, which is associated with memory function and post-perceptual processing in abstract narrative stimuli. This finding suggests that the N600 potential plays a crucial role in processing and encoding narrative information in pictures. In addition, we were able to classify the narrative context of stimuli into four different levels of narrativity. This study holds great promise for further understanding the levels of narrativity in pictures and uncovering EEG-biomarkers.

Paper F: Exploring Cognitive Processes in Narrative Engagement: An EEG study on interconnected attention, immersion, and memory at varying narrativity levels.

In this study, we investigated the relationship between narrativity and cognitive processes using electroencephalography (EEG) and behavioral measures. We aimed to extend previous research by exploring the modulation of neural reliability, self-reported engagement, and memory across subjects using four levels of narrativity (abstract, low, medium, and high) in response to picture stimuli presented to 27 participants. The hypothesis was that higher narrativity levels correspond to increased engagement and memory scores, building upon prior findings. We employed a within-subject design with one independent variable of "narrativity level", containing four factors abstract-level, low-level, medium-level, and high-level of narrativity. Each participant faced 40 paintings from different levels of narrativity, and the paintings were presented in a randomized order across narrativity levels. Each stimulus showed a white fixation cross on the black background for 6 seconds as a baseline. Then a painting was shown for 15 seconds. Finally, the participants were guided to answer three questions for each painting to evaluate narrative understanding, emotional engagement, and attentional focus. The results suggested that narrativity levels modulate self-reported measurements and inter-subject correlation (ISC), showing a significant increase in ISC from low to high narrativity levels. The scalp distribution of ISC components indicated widespread cortical involvement, and the study successfully predicted memory scores based on ISC. For narrative understanding, the abstract-level has the minimum average score of understanding, and the low-level of narrativity has the maximum average score of understanding. For emotional engagement and attentional focus, a higher narrativity level leads to higher engagement, as the statistical tests revealed a significant increasing trend of scores from the abstract-level to the high-level. However, the memory test results showed no significant difference between different narrativity levels. In conclusion, we represented one of the first cognitive investigations to define narrative as a spectrum, using a framework to quantify and validate narrativity levels. The findings shed light on the interconnectedness of attention, immersion, and memory in narrative engagement, and future research could explore the predictive power of multimodal stimuli on memory scores using ISC analysis, providing valuable insights into the brain mechanisms involved in processing narrativity levels and memory.

Paper G: Digital Narratives in Extended Realities. Road mapping Extended Reality: Fundamentals and Applications.

In this paper, we explored the implementation of digital narratives in extended realities (XR) and the challenges associated with it. We mentioned that XR technologies are increasingly recognized as expressive media with unique qualities for narrative representation. We discuss the concept of immersion in XR and its relationship to narrative engagement. We emphasized that immersion in XR encompasses more than just perceptual and spatial aspects, but also includes narrative immersion, which refers to how users become involved with the story and its world. Moreover, we highlighted the "narrative paradox" discussed in the Interactive Digital Narratives (IDN) community and emphasized the broader connotations of the term "immersion" in IDN compared to the XR domain. It is crucial to highlight that XR offers new possibilities for narrative engagement, but also presents challenges related to agency, embodiment, narration, artificial agents, and AI. There are several key challenges in implementing digital narratives in XR. These challenges include maintaining a balance between interactivity and immersion, ensuring user agency and meaningful choices, designing effective narrative structures for XR, creating believable and engaging artificial agents, and integrating AI technologies to enhance narrative experiences. We also highlighted the need for interdisciplinary collaboration between researchers and practitioners from fields such as storytelling, game design, human-computer interaction, and cognitive science to address these challenges. Furthermore, we provided examples of application domains where XR narratives are being utilized. These domains include games, serious games, cultural experiences, healthcare, and immersive journalism. We highlighted the potential of XR narratives in creating engaging and immersive gaming experiences, training simulations for healthcare professionals, virtual cultural heritage experiences, therapeutic interventions, and immersive journalism for impactful storytelling.

Paper H: Conscious and Non-conscious Responses to Branded Narrative Advertising Investigating Narrativity Level and Device Type.

This paper is the second paper from the high level versus low level on narrativity, described in “Paper C”, but with a specific focus on the marketing field as required by the RHUMBO project. In this paper, we aimed to investigate the effects of narrativity level and delivery modality (PC vs. VR) on advertising and brand responses. As mentioned in paper C, we used a combination of self-reported measures and neurophysiological metrics to record participants' responses to ads with varying levels of narrativity and delivery modality. We found that high narrativity-level ads were more effective in engaging participants and eliciting positive emotional responses. The self-reported measures showed that high narrativity level ads performed better in most ad-related metrics, except for one measurement. The most noticeable and consistent impact of narrativity level across brands was on Ad Entertainment. Participants liked that the ads with a clear storyline were entertaining in addition to selling the product or service. Regarding brand-related metrics, we found that Brand Attitude and Brand Interest did not differ across narrativity levels. However, the low-narrativity ads produced better Brand Trust for all six brands. These ads showed product features and options explicitly, which seems to have increased the ads' credibility. We also found that delivery modality had an impact on ad and brand responses. Video ads were more effective in eliciting emotional responses and improving brand recall compared to static ads. However, the neurophysiological metrics did not reveal any significant differences between the two delivery modalities.

CHAPTER 4. CONCLUSION AND FUTURE WORK

This Ph.D. project was conducted within the European Union project i.e.: RHUMBO (Marie Skłodowska-Curie Actions) with the aim of investigating the specific aspects of narrative cognition, the brain reaction while the participants are exposed to the different contexts of the narrative. We started by reviewing the previous literature in the narratology field and what have previous researchers done to characterize narrative cognition. Then we pointed out that there are few studies that tried to bridge the gap between high-level narratological concepts and low-level EEG metrics. The existing literature has assumed the narrative as an either-or concept and has not dealt with the subjective differences. Therefore, we focused on three main points in this PhD project and provided solutions for them.

First, we have developed a narrative framework that looks at the concept of narrativity as a quality of being narrative rather than an either-or concept. We started by defining different levels of “narrativity”. In the first experiment, we defined two levels of narrativity (low versus high). In a later experiment, we divided the scale into four levels (abstract level, low level, medium level, and high level of narrativity). Moreover, we developed a framework to validate these predefined levels. Reviewing the conceptual papers in the narrative field, we prepared a set of questions related to narrative artifacts (either videos or paintings). Then we published the artifacts and the questions online and asked participants to respond to the questions corresponding to the artifacts. Gathering all the responses and evaluating the agreement among the participants, we assigned the narrative artifacts to pre-defined levels. In this way, we validated our frame-work for levels of narrativity with a random audience (papers C, E, and F). Gathering the experiences that we had from such a framework, we developed an experiment with a more ecologically valid, continuous narrative trajectory which included a narrative dramatic arc. The framework consists of identifying a narrative plot for a video and defining the different phases that build-up such a plot, then we validated the plot with an experienced audience, specifically validating the start and the ending of each phase of the dramatic arc. Next, we asked another group of participants to watch the video and rate their engagement continuously and related the scores to different parts of the video. Finally, we showed the video to the participants while collecting their EEG data and we combined all the gathered information and analyzed them together (paper D).

Secondly, we developed metrics by which we were able to characterize narrative cognition. Previous studies in the area of narrative cognition have used EEG metrics such as ERP and PSD which are useful to characterize the discrete narrative artifact. The problem with those metrics is that if we want to utilize them, we need to either repeat the stimuli multiple times or window the EEG signals and average over the windows. This would lead to less ecologically valid experiments and a loss of information. In this Ph.D. project, inspired by other fields, we developed metrics that enabled us to characterize continuous narrative artifacts (ISC, dFC, and graph theoretical metrics). Using these metrics, we no longer need to repeat the stimuli or average over the signals, rather, we slide a window to cover the whole narrative experience and then directly use the continuous metrics to characterize specific aspects of narrative cognition.

Third, we addressed a common issue in the narrative field which is subjective differences. In narratology, one thing is the implication of a narrative artifact Considering the writer's perspective is one aspect, while its genuine impact on the audience is another matter. In theory, numerous factors can impact this alignment or absence thereof, such as inadequate story development (including the narrative itself and/or its dramatic structure), subpar portrayal of the narrative (its adaptation into a specific medium), the degree of familiarity with the story or its archetypal model/genre (i.e., banalization), etc. Therefore, a successful narrative delivers the author's meaning equally to all the participants. However, due to many reasons such as semantic memory, the audiences do not get the narrative in the same way. This fact would lead to a biased evaluation of the defined metrics. To solve this issue, we developed methods that are robust against the subjective differences. For example, ISC uses the EEG of all the subjects together to provide an index of how similar the participants were thinking. In other words, it measures the neural similarity across subjects. Moreover, all the metrics were then tested using a machine learning algorithm by leave-one-out approach. In this approach, we train the model using the information from all the subjects (except the left-out subject). This would lead to a model that has already considered subjective differences and provides an evaluation that is robust against them.

In the context of the RHUMBO project which was intended to use advanced biometric signal processing as a new paradigm to improve the knowledge that implicit brain processes have in human decision-making. The main application of this Ph. D. project is in the neuromarketing field. Developing a continuous narrative framework and EEG metrics to characterize it would be a helpful tool to characterize human behavior in real-life situations when confronted with narrative artifacts. The application of narrative studies in neuromarketing involves using neurophysiological tools to measure unconscious cognitive and affective responses to narrative advertising, particularly in emerging mixed reality environments. By investigating the effects of narrativity level and medium type on advertising and brand responses, neuromarketers can gain a deeper understanding of how consumers process and respond to different types of ads. This information can be used to optimize ad content and delivery for maximum impact. Overall, the combination of self-reported and neurophysiological metrics provides a more comprehensive understanding of consumer responses to narrative advertising, which can inform marketing strategies and improve advertising effectiveness. Moreover, revealing such information allows us to have a better understanding of humans, in real decision-making situations. Besides these fields of applications determined by the objectives of RHUMBO, this project can also provide tools for investigating narrative cognition and persuasion in other domains such as pedagogics, psychology, health, and social issues.

Future studies are encouraged to focus on two main areas.

a) We mentioned that to develop a narrative framework in mixed reality systems, we need to build up the steps one by one to reach an ecologically valid framework that does not have lab situation limitations (such as stimuli repetition). In this Ph. D. project, we have developed all the requirements that researchers can use to build and investigate a narrative issue, characterize it, and further relate it to specific cognitive faculties. Therefore, future studies are strongly encouraged to implement this framework in mixed reality systems, since it has considerable advantages (see section 1.2.2). Within this Ph. D. project, we have partially implemented our framework in mixed reality systems, but due to some practical limitations, we could not test them. Here we briefly explain the way we developed our framework in VR environments to give an idea for future studies. In the first study, we implemented our already tested levels of narrativity framework in a shopping environment. The experiment intended to involve a role-playing situation about purchasing material for a camping trip from a virtual supermarket. Any of the characters had different characteristics and the participants should have made decisions to buy specific materials for any of the characters based on a shopping list considering their personalities. The experiment had four levels of narrativity which we translated to four different scenarios. Followed by an introduction phase where the participants would be expected to know the characters, and they would be exposed to each scenario before entering the virtual supermarket. In the first scenario, participants would enter the virtual supermarket without any previous exposure (non-narrativity). In the second scenario, they would be exposed to a story where purchases had causal links together (low narrativity level). For example, if they chose to buy wine rather than beer, they must have bought cheese instead of chips. In the last scenario, the decisions made by the participants could have a potential argument (high narrativity level). For example, if the participant chooses to buy wine for a character, the other character will get mad since they have a wine allergy.
   A second experiment which is designed as a further development of the present Ph. D., consists of a full narrative dramatic arc where the participant enters the VR environment and is exposed to a story with a full narrative trajectory following the dramatic art plot and its phases. In the exposition phase, the character and their mother drive a car toward their grandmother's house. They arrive at grandmother's place and the crisis starts with grandmother mentioning that the neighbor complaining about the tree that is

passing the border of the house, but the tree is grandfather's memento which passed away last year. The climax phase starts when the participants enter an argument with the neighbor. In the falling the participant and the mother find a way to solve the problem with the lawyer and finally, in the denouement phase, they enter into an agreement with the neighbor. This was the first condition of the experiment. In the second phase, we put some violations on each phase to see how the violation in the narrative effect the cognitive processes.

b) A second area of focus could potentially develop new metrics to characterize narrative cognition. One of the metrics we developed in this project was dFC, which did not overcome the subjective difference by itself. To address that, we used a leave-one subject in our SVR approach and fed the dFC features to overcome the subjective differences. Another approach that future studies are encouraged to use is the dFC latent features that we explained in section XX. The reason that the dFC latent feature overcomes the subjective differences themselves is that this approach merges the dFC of all participants first. Then it clusters the big matrix obtained out of such concatenation and extracts the latent features based on the identified cluster cores.

CHAPTER 5. REFERENCES

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