Name, institution, and contact details of the applicant (one person only) and a list of the scientists or institutions involved in the research project (max. 2 A4 pages)

CVs and lists of publications need not be submitted.

PD Dr. rer. medic. Susanne Weis

Simon

INM-7: The proposed work is embedded in a multidisciplinary working team combining knowledge in the field of neuropsychology, structural and functional MRI analysis, computational neuroscience and machine learning.

Dr. Kaustubh Patil, head of the working group “Applied Machine Learning”

Rick Betzel is an associate professor at the Psychological and Brain Sciences Department of Psychological and Brain Sciences at Indiana University Bloomington, USA. He is an expert in principles of time-varying functional network reconfiguration and its relationship to ongoing cognitive processes and one of the developers of the edge time series approach which we will employ within the project suggested here.

b) Project title and description (max. 5 A4 pages); references can be provided on further pages.

Dynamic Cognition: Using movies to disentangle Sex Differences and Hormonal Modulation of Functional Brain Organization

Project Description

Functional brain imaging techniques, in particular fMRI have been widely used to investigate sex differences in the brain. Such differences in structural and functional brain organization play a crucial role in healthy human brain development, aging, as well as the manifestation of psychiatric and neurological disorders [1-3]. Consequently, an understanding of sex differences in the human brain and their underlying mechanisms, as well as their modulation by fluctuating steroid hormone levels is critical for understanding both normative behaviour and psychopathology.

In the present proposal, we will employ novel methodology utilizing naturalistic viewing (NV), i.e. watching of movies clips in the scanner, to broaden our knowledge of sex differences in the brain and their hormonal modulation. While it is common knowledge that women and men often react differently to complex scenarios in films - think of how a couple might debate a movie's emotional impact after leaving the cinema - our study delves deeper than these everyday observations. Instead of relying on stereotypes such as 'women like emotional scenes, men like action', we will analyse in detail how brain activity and functional connectivity (FC) differs when women and men watch various movie scenes. This could reveal, for example, that women process subtle social cues in dialogues differently from men, while men might react more strongly to visual hints in action scenes that foreshadow danger. Through a thorough analysis of females’ and males’ brain responses to a variety of different movie scenes, we aim to develop a well-founded understanding of cognitive sex differences that goes beyond what we think we know from everyday life.

So far, our understanding of sex differences in the brain is still far from complete. While there is some agreement on the existence of sex differences in specific cognitive domains like language and spatial processing, some researchers argue that female and male brains are altogether more similar than different [4] and that the overlap between the sexes is larger than their differences. Importantly, neuroimaging research on sex difference has so far only been able to capture certain aspects of these differences.

Classically, sex differences in the brain have been studied using task-based (TB) fMRI with tightly controlled tasks, offering insights limited to specific cognitive domains. More recently, resting state (RS) fMRI has revealed sex differences in intrinsic brain organization, yet it only captures a narrow aspect of functional neuroanatomy, i.e. intrinsic functional brain organization.

What remains largely unexplored is how females and males differ in brain responses to complex, multimodal stimulation resembling real-life experiences. This gap is likely due to a lack of suitable methodologies to capture such dynamic and multimodal processing and the variety of FC patterns that might distinguish females from males.

The present proposal aims to contribute to closing this gap in knowledge by applying the NV approach—watching movie clips in the scanner—to examine sex-specific brain responses in ecologically valid contexts. Unlike rather artificial and simplified TB tasks or the passive nature of RS, NV offers rich, time-evolving stimulation, allowing for the study of dynamic brain states across diverse scenarios. This method better reflects everyday cognitive and emotional challenges and may uncover novel sex differences in functional brain organization.

By delineating how females and males process complex environments our findings can add a crucial new dimension to the understanding of cognitive sex differences. Psychologically, these insights deepen our understanding of normative sex differences; clinically, they may help clarify why certain psychiatric and neurological disorders manifest differently in men and women. Such knowledge can potentially enhance diagnostic accuracy, inform personalized treatments, and support the development of sex-specific healthcare and education strategies.

Throughout the proposal, for ease of reading, the term “sex” will refer to the self-reported sex and appearance of the participants. At the same time, we fully acknowledge that “gender identity”, i.e. the subjective identification of an individual as female, male, or one of the other gender identities which might be also fluid, also play important roles, which however, are beyond the scope of the present project.

Studying sex differences with TB and RS fMRI

The classical approach of TB fMRI in the study of sex differences employs carefully designed and temporally controlled cognitive tasks during which brain activation is recorded. Specific paradigms are employed to evoke brain states tightly coupled to the task at hand. Fixed and temporally controlled stimulation enables pooling of stimulus-locked data across participants and averaging across groups. Such paradigms are designed to delineate “typical” brain activation patterns that are shared across participants. Due to the highly controlled and artificial nature of the tasks, ecological validity of task-related fMRI is usually very low. Moreover, the vast majority of TB examinations of sex differences comprise rather small group sizes, limiting generalization of the findings. A fundamentally different approach of studying sex differences in the brain is RS fMRI. Here, fMRI data is acquired while subjects relax in the scanner with no specific task demand and no visual or auditory stimulation. RS offers advantages over TB fMRI. Firstly, acquisition of RS data is easy and universally applicable to a wide range of participants as very little task compliance is necessary. In the same vein, RS fMRI is independent of task performance, reducing the influence of this critical confound. Importantly though, RS fMRI only reflects the brain in a specific state, which has commonly interpreted as intrinsic brain organization and thus constitutes a trait rather than a state. Moreover, while a state of free mind wandering happens often in real life, examination of RS cannot tell us anything about the “brain in action”, i.e. when encountering complex dynamic experiences and richly textured contexts. Clearly, further research is needed. As argued above, traditional methodological approaches such as TB and RS fMRI paradigms might not be ideally suited for studying the brain “in action”. Thus, in the present proposal, we suggest movie watching as a novel approach to further elucidate sex differences in the brain.

Naturalistic Viewing

NV is a newly emerging approach to fMRI data acquisition. In contrast to more classical experiments in cognitive neuroscience, which are usually built on reducing complex phenomena down to their simplest form and generally entail static, unimodal, and artificial stimuli, NV focuses on cognitive processes in dynamic, temporally extended, naturalistic contexts, which are much more akin to situations which the brain must deal with in real life. In NV tasks, participants in the scanner are presented with naturalistic material like movies. For the participants, there is no other task demand rather than watching the clips. Like RS fMRI, data acquisition applicable to a wide variety of subjects, as it is largely independent of task compliance and task performance. On the other hand, like TB paradigms, NV offers an engaging task for the subject and thus avoids boredom in the scanner. Importantly, as opposed to RS, all participants are exposed to the same stimulus, for which content and timing is known and can be used in the analyses. NV approaches offer complex, dynamic and ongoing stimulation similar to experiences in everyday situations, where low-level (audiovisual) and high-level (cognitive and emotional) content vary fluidly, creating a multimodal and immersive experiment [5]. A number of studies have employed NV designs to study individual differences in healthy and patient samples [6, 7] and it has been suggested [8] that NV offers the opportunity to capture dynamic neural processing in ecologically valid contexts [9]. Furthermore, NV has been shown to improve reliability and individual identifiability over RS [10, 11] with a recent study from our lab [12] showing that the use of NV enhances the detection of FC patterns that are unique at the individual level. An additional advantage of NV is the broad set of analyses to which the data lend themselves. Basically, any method that can be applied to RS fMRI data can be adapted to NV paradigms. On top of that, analysis methods based on time-locked stimulation across participants can be used and put into relation to the known dynamic content of the movies.

Using NV to study sex differences

While the general idea of using NV to experimentally manipulate brain state and enhance individual differences has been considered [13], to our knowledge, no study has yet used brain activation and FC patterns evoked by NV to systematically examine sex differences. This is surprising, given that NV paradigms effectively engage the brain in complex, multimodal, and dynamically evolving scenarios, thus potentially bringing out sex differences that remain undetectable in TB or RS fMRI studies [14]. In a previous publication [14], we have compared the potential of movies for the study of individual brain differences to what running on a treadmill is to the heart during a cardiac stress-test, i.e. to potentially provide a standardized way to study the whole organ while it works to compare function across different levels of intensity and demands. In the present context, this means that NV can be expected to reveal sex differences in the brain that so far have been unobservable, since NV data encompass an extensive range of dynamic real-life situations, such as social interactions, recognition of faces or perception of emotions [5]. While isolated cognitive processes as examined in TB fMRI might not reveal significant sex differences, the complex interplay of these processes - as engaged during movie watching - could highlight more pronounced differences between women and men. This underscores the value of using naturalistic stimuli to uncover subtle but meaningful variations in neural processing that might be missed in more controlled, simplified experimental paradigms. Using careful annotations of the movies used in the study, it is also possible to identify which features of a given scene are particularly relevant to evoking sex differences in complex experiences and to identify brain networks that differ most between females and males during these experiences.

The present project

Altogether, in this proposal, we aim to employ novel methodology utilizing NV paradigms to expand our understanding of sex differences in the brain and their dynamic hormone related modulation. This approach has the potential to elucidate sex-specific neural mechanisms in response to the complex and dynamic content of movies and to reveal nuanced sex-specific distinctions in brain function that may not be apparent in more constrained experimental paradigms or everyday observations. Our methodology leverages the ecological validity of movie stimuli to probe complex, multimodal cognitive processes in a controlled yet naturalistic setting. Through advanced neuroimaging techniques and sophisticated data analysis methods, we anticipate uncovering subtle yet significant sex-based variations in neural activity and FC and their hormone driven modulation that can inform our understanding of broader cognitive and behavioural differences between females and males. To this aim, we will first consider temporally aggregated FC evoked by movies over the duration of several minutes. Subsequently, we will further disentangle which specific events evoke sex differences and examine differences in the brain networks caused by such events. Furthermore, we will examine how the brain’s response to the evolving narrative of the movies differs between the sexes and is modulated by the dynamic influence of hormonal fluctuations.

The project's comprehensive approach of examining temporally aggregated as well as time resolved FC, network dynamics and brain activity patterns provides a multi-faceted view of sex differences in the brain and their hormonal modulation, which can have implications for understanding sex differences in cognition, behaviour, and susceptibility to certain neurological and psychiatric conditions.

Previous work by the applicants

The applicants have a longstanding expertise in brain function and FC, particularly regarding all aspects of the planned work, i.e. sex differences [15-22], hormonal influences [15-19] and NV [10, 11, 23-25] approaches. We also have extensive experience in studying intra- and inter-individual differences in behaviour [26-28] and FC during TB [15-18] and RS fMRI [19-22], often using machine learning (ML) approaches [20-22, 29]. We have conducted multiple NV A diagram of a brain

AI-generated content may be incorrect.fMRI studies [10, 11, 14, 25] and developed a novel analysis method for such data [24].

A group of brain models

Description automatically generated with medium confidenceA close-up of a brain scan

Description automatically generatedOur previous work showed that sex hormones, particularly oestradiol and progesterone, dynamically modulate FC and functional asymmetry across the MC [15-18] with hormone related changes in intra-hemispheric FC [17] and greater left-hemisphere dominance during low-hormone phases [18] (Fig 1), indicating that hormonal fluctuations alter both lateralized activations and communication between the hemispheres [17]. RS FC was also found to be sex-specific and modulated by hormonal fluctuations in women (Fig 2), with some regions showing stable sex differences and others showing hormone-driven changes only in women [23].

Fig. 1: Sex x repeated test interaction of inter-hemispheric inhibition (Weis et al., J Neurosci, 2008)

Fig. 2: Sex differences in RS FC are modulated by fluctuation hormones (Weis et al., Brain Cogn, 2019)

More recently, we employed a ML approach to identify brain networks supporting successful sex classification from RS data. We identified regionally specific brain networks underlying successful classification of novel subjects’ sex which, importantly, generalized from the training sample to an independent sample (Fig. 3) and showed that predictive power is most pronounced in higher-level cognitive regions involved with language, social cognition and emotion processing [20].

Fig. 3: ROI-based sex classification shows high accuracies for (a) within sample CV and (b) across sample classification (Weis et al., Cerebral Cortex, 2020)

A diagram of different types of female and male

Description automatically generatedWe further examined methodological aspects of using ML for sex classification studies by examining the bias of such models due to brain size differences between females and males (Fig. 4). Our results showed that accounting for brain size bias yields models that accurately classify both cis- and transgender individuals [22]. Further work revealed that classifiers trained on diverse, compound datasets generalized better than those trained on single-site samples [21].

A diagram of a brain

AI-generated content may be incorrect.A close-up of a diagram

AI-generated content may be incorrect.Our lab also pioneered NV analysis methods. We recently developed the topography-based predictive framework (TOPF) [24], which identifies individual-specific evoked activity topographies in a data-driven manner and examines their behavioural relevance using a ML predictive framework (Fig. 5). TOPF effectively and stably captures individual differences in evoked brain activity and successfully predicts phenotypes across cognition, emotion and personality. Moreover, TOPF exceeds FC based approaches in prediction performance with the identified predictive brain regions being neurobiologically interpretable.

Fig. 5: TOPF captures individual differences in brain activity and successfully predicts phenotypes across cognition, emotion and personality (Li et al., Neuroimage, 2023)

Fig. 4: Brain size biases sex classification accuracies (Wiersch et al., Scientific Reports, 2023)

Our recent findings [23] demonstrate that stimulus type strongly influences prediction accuracy and relevant brain features, underscoring the importance of stimulus selection in NV studies (Fig. 6). Additional work showed that NV improves individual identifiability over RS based on FC [10] and yields higher test-retest reliability for graph metrics, depending on stimuli and networks [11]. Our studies strongly encourage the use of NV to increase reliability but emphasize the need to carefully select the appropriate stimulus for the respective research question. Another study [25] highlighted the critical role of narrative and emotional content in synchronizing brain responses across individuals. In preliminary work using TOPF [24] on NV data from the HCP 7T dataset [30], we achieved up to 80% accuracy in sex classification on single movie clips. Classifier performance depended on clip length and content, with social content and familiarity enhancing accuracy. Predictive regions were linked to emotion, language, and higher cognition. These promising findings await further validation over the course of the present project.

Fig. 6: Movie features influence phenotype prediction performance (Li et al., HBM, 2025)

# Objectives and work programme

## Anticipated total duration of the project

The work described in the current proposal is planned for an initial duration of 36 months.

## Objectives

The overarching goal of the proposed project is to complement existing research on sex differences by employing a NV approach. This method promises new insights into sex differences in the brain response to complex and dynamically evolving situations akin to what the brain has to deal with in real life. Results can go beyond existing studies based on both TB or RS approaches and promise novel insights that could so far not be achieved with existing research approaches. Specifically, we will examine which types of complex situations as depicted in the movie stimuli result in most pronounced sex differences. In the next steps, we will further disentangle which events within the movies’ narrative drive these sex differences and examine how females’ and males’ brains respond differentially to the evolving narrative of the movies.

Importantly, we will include OC use and measures of fluctuating steroid hormone levels in the analyses to be able to account for hormone related variability and disentangle underlying sex differences from dynamic hormone driven variability of functional brain organization.

We expect this novel approach to the study of cognitive sex differences together with the project's comprehensive approach of examining temporally aggregated FC, event-related responses, network dynamics and brain activity as well as hormone related variability to provide important new insights into the multi-faceted spectrum of sex differences of the brain in action.

Firstly, in work package (WP) 1 we aim to go beyond existing results on sex differences in the RS by examining sustained FC over the course of a variety of movies of several minutes length. Using a temporally aggregated FC approach as commonly used for RS data, results of this WP will identify sex differences in “action brain states” and their underlying brain networks.

In WP 2, we will then employ a time resolved FC approach to identify temporally specific events driving sex differences in the experience of complex situations. This approach makes use of the know dynamics and content of the movies. Detailed annotations of the movie content will be used to characterize the type of situations that drive sex differences together with revealing sex specific cognitive strategies when encountering such situations.

In WP3, rather than looking at temporally aggregated or time resolved FC patterns we will examine the brain activation invoked by the movies. In particular, we will extract (within each brain region) typical female and male brain responses to the dynamically evolving movie content. This approach complements results from WP1 and WP2 through an understanding of how females’ and males’ brains respond differentially to the evolving narrative of the movies.

While WPs 1 – 3 will focus on underlying sex differences by controlling for hormone levels as covariates of no interest, in WP4, we will explicitly examine the influence of fluctuating levels of steroid hormones on brain activation and FC patterns. To account for variations induced by OC, these analyses will be done separately for naturally cycling females, females using OC and men. Results of this WP will grant important insights into how hormonal fluctuations modulate our experience of complex and multimodal experiences on top of underlying sex difference.

## Work programme incl. proposed research methods

### Data: The Ju-MOVIES dataset

All planned analyses in the present project will rely on an NV dataset that has been collected in our lab over recent months and will continue to be expanded during the course of the project. While data have already been collected, it has so far not appeared in any peer reviewed publication. The study was approved by the ethics committee of the Heinrich-Heine-Universität Düsseldorf (grant numbers “2018-100-Drittmittel”, “2018-100\_1-andere Forschung erstvotierend”, “2018-100\_2-andere Forschung erstvotierend” and “2018-100\_3-andere Forschung erstvotierend”).

The paradigm comprises seven movie clips of about 8 – 10 minutes in length, which are all excerpts from Hollywood movies (“Dirty Dancing”, “Scream”, “Dead Poets Society”, “Forrest Gump”, “Dead Man Walking”, “Life is Beautiful”, “The Good, the Bad, the Ugly”), because of their engaging and complex nature. The specific movie stimuli were chosen to cover a variety of social interactions and complex situations as well as multifaceted emotions evolving over the course of the movie to match the complex nature of real-life experiences. Considering that viewers lack the context of the entire movie, each stimulus was chosen to be long enough for the viewers to understand the situation, empathize with characters and follow the evolving narrative. Additionally, participants watch a compilation of 12 short movie clips (“Short Sequences”), which were again taken from Hollywood movies (“Gone Girl”, “Seven”, “Sex of Angels”, “The Hobbit – Battle of the Five Armies”, “Lost in Translation”, 2 clips from “Blue is the warmest color”, “Star Wars – Revenge of the Sith”, 2 clips from “Short Term 12”, “Shining”, “When Harry Met Sally”), and completed two RS scans of about 9 minutes length with their eyes held open.

So far, we collected data of 125 healthy participants (63 males, age 18 - 35 years, mean age = 24.33 years). To ensure the validity of the ML analyses that are central to the studies outlined below, we aim to increase the size of the dataset by another 160 participants over the course of this project. While in general it is complicated to predict how many samples are needed for ML models to perform successfully, with roughly 300 samples the size of our dataset will exceed the HCP 7T subset (n = 184) of the HCP S1200 release [30], which also comprises NV data and has repeatedly been shown to yield accurate ML predictions [24, 31]. To collect the maximum amount of data we will not specifically time the measurements according to MC phase in women. However, we will regularly check for a broad spread of hormone status across the sample and put particular effort in collecting data from underrepresented phases.

All fMRI data are acquired on a Siemens 3T Prisma scanning (Siemens, Erlangen, Germany) with a 64-channel head coil at the Imaging Core Facility of Research Centre Jülich, using a T2w multiband echo planar imaging sequence with the following parameters: repetition time (TR) = 980ms, echo time (TE) = 30ms, flip angle = 70°, field of view (FOV) = 207 × 207mm, voxel size=2.2 x 2.2 x 2.0mm3, number of slices: 64, multiband acceleration factor=4, phase encoding direction=AP, FoV=207mm). A mirror fixed on the head coil allows participants to see a screen used to display the movies. In-ear headphones are used for ear protection and to deliver the movie sound. Additionally, a structural T1w image is acquired using an MP-RAGE sequence (TR=2000ms, TE=2.45ms, TI=900ms, flip angle=8°, FoV: 256mm) yielding 1mm3 voxels.

Saliva samples are collected from each participant and levels of cortisol (μg/dl), oestradiol (pg/ml), progesterone (pg/ml), and testosterone (pg/ml) are analysed by a specialized laboratory. Control for fluctuating hormone levels is essential for a meaningfully interpretation of potential sex differences in functional brain organization and hormonal data will provide the bases for all analyses planned in WP4. Furthermore, data OC intake is noted for female participants.

A graph showing the different colored lines

AI-generated content may be incorrect.To characterize the movie stimuli in more detail, emotions perceived by viewers of the movies were assessed by 44 German participants (23 males, age 20-30 years, mean age 25.05 years) who watched all movie stimuli while simultaneously rating six basic emotions (happiness, fear, surprise, sadness, disgust and anger [32]). Rating were collected by the ReMoTa toolbox (Real-time Movie Tagging v0.0; [33]). Participants watched the movies on a laptop and rated their feelings by use of the keyboard. All emotions were rated simultaneously on a scale from 0 to 100 at a sampling rate of 10hz. The emotion ratings (example in Fig 7) confirmed the multifaceted and diverse emotions elicited by the different movie stimuli. In a further annotation (Ju-MOVIE-An), two independent raters quantified the following features: faces, bodies, male / female presenting characters, ethnicity of characters, presence of children, adults, crowds, hands, buildings, vehicles, food, landscapes, animals, plants, movement, social interactions, place (inside or outside / urban vs. non-urban), time of day (day or night), weather, presence of music and camera movements. During the course of the present project, we aim to extend these annotations with more independent raters.

Fig. 7: Exemplary emotion annotation for one of the movie stimuli.

### *WP 1: The Brain in Action – The Naturalistic Viewing Action State (NV-*AS)

### Several studies have shown that sex classification based on RS FC can achieve high classification accuracies [20, 21, 34-37] by capturing temporally aggregated FC patterns evoked over a sustained state of free thought or mind wandering. Since these RS brain patterns are independent of any external stimulation, they are often taken as a proxy for intrinsic brain organization, and in that sense, constitute more of a trait rather than an actual state.

The present WP aims to supplement existing results on sex differences in the brain by examining temporally aggregated FC patterns induced by the complex narratives presented in the movies. In contrast to RS, we expect movie induced brain patterns to represent states that are strongly dependent on the content of the movies. As this content is known, it can be used to characterize evoked FC patterns and sex differences between them. Thus, in this WP we will consider sustained brain “action states” (ASs) evoked by different movies and compare sex classification accuracies based on different naturalistic viewing ASs (NV-ASs) to RS. Since sex differences in NV-ASs depend on movie content, annotations the content will be employed to characterize the evoked brain NS-ASs and sex differences between them. Thus, this WP will provide insights into which kind of situations evoke particularly prominent differences between females and males. Here, we are looking at sex differences in the overall experience of complex situations, which is different both from TB studies looking at sex differences within specific cognitive tasks and from RS which mostly reflects intrinsic brain organization. We assume, that putting the brain into action while experiencing different complex situations should bring out differences between females and males more strongly than unrestricted and thus uncontrolled free thought can [38, 39].

### To compare enduring NV-AS to RS and amongst different movies, we will employ a similar approach as in our previous work [20]. Briefly, after parcellating the fMRI data into non-overlapping parcels based on an established parcellation (e.g. [40]) a mean activation time course will be computed for each parcel and correlated with those of each of the other parcels. Then, for each parcel individually, the FC pattern with the rest of the brain will be used as features to train a sex classifier for which classification accuracy will be determined by use of a cross validation (CV) approach. This procedure results in a spatial map of sex classification accuracies across the brain (see Fig 3) for RS and each NV-AS (i.e. each movie). Importantly, and in contrast to the majority of previous studies, we will include hormone levels and OC status in women as confounds into all prediction analyses in WP1 to ensure that results delineate actual differences between the sexes, rather than hormone related variability. In doing so, we will take particular care to control for confound leakage [41], which might bias results of the prediction analyses.

WP 1.1: Comparing sex classification accuracies between RS and NV-ASs

### As a first step, within each parcel, sex classification performance (across CV folds) will be compared between RS and NV-AS (averaged across all movies) by use of corrected resampled t-tests [42]. Higher classification accuracies during NV (compared to RS) will reveal cognitive sex differences that are specific to the brain in action rather than to its intrinsic organization. In addition, the spatial distribution of highly discriminative parcels in NV will highlight the brain networks underlying these sex differences in the NV-AS. Cognitive domains related to the identified brain networks can be characterized by use of functional decoding [43]. While sex differences have often been reported in the DMN for RS [20, 44], for NV-AS, we expect sex differences in higher cognitive or task-general networks [45]. Furthermore, we expect sex classification based on NV-AS to outperform RS, as similar effects have been observed for other phenotypes [13, 39] and NV has been shown to increases individual identifiability over RS [10].

WP 1.2: Which movie features drive sex classification accuracies?

### To further examine which kinds of complex situations maximize sex differences in the brain, we will characterize each movie clip by several visual and auditory features across the duration of the movie clips. These will comprise low-level features like mean motion energy [46], visual brightness and auditory loudness, high-level features like number of faces, social interactions and words, which can be automatically extracted [47, 48], and further movie features that have been acquired in Ju-MOVIE-An. We will then compare sex classification accuracies across the whole brain between the eight different movies clips by use of a multiple regression approach, which will delineate which movie features drive classification performance for each brain parcel. As higher classification performance indicates more pronounced differences between the sexes, this procedure will result in a “movie feature profile” explaining which features of the movies result in most pronounced sex differences. By clustering brain parcels according to their movie feature profiles, we will identify brain networks in which sex differences are conjointly driven by specific features of the movies. We hypothesize that certain brain networks will comprise specific cognitive domains, in particular those that have been identified in classical group studies, which identified sex differences in cognitive domains like language and spatial cognition [49, 50]. Other networks can be expected to comprise more generalized and non-specific cognitive resources which are independent of the specific situation [45]. We expect domain-specific brain networks to overall achieve higher sex classification accuracies than domain-general networks.

### In an exploratory approach, we will compare the expressions of these networks in females and males by computing the first principal component of network FC patterns in females and males separately, thus identifying the “typical” female and male brain network pattern for each movie feature cluster. An exploration of these sex specific movie feature networks should help elucidate sex specific cognitive strategies in response to complex life-like situations.

Main Goal: Characterize sex differences in the NV-AS to reveal situationally modulated sex differences that may not be evident in RS.

Hypothesis 1 - State-Dependence of Sex Differences: Sex classification accuracy will be significantly higher during NV-ASs than during RS, reflecting the enhanced expression of sex-specific FC patterns during content-driven engagement over intrinsic, unconstrained thought.

Hypothesis 2 - Brain Region Specificity: The spatial distribution of classification accuracy across brain parcels will differ between RS and NV-ASs, reflecting distinct sex-specific FC patterns under intrinsic (default mode regions) versus context-evoked (higher-order cognitive and task-general networks) conditions.

Hypothesis 3 - Content-Specific Modulation: Sex classification accuracy during NV-ASs will vary across movie clips and be related more to high-level features such as social interaction, number of faces, or dialogue than low-level features like brightness or loudness.

Hypothesis 4 - Domain-Specific Network Associations: Parcels showing significantly higher classification accuracies for NV-AS than RS will be associated with cognitive domains like language, emotion, and social cognition, which have been previously linked to sex differences.

Open Question: Will sex specific movie feature networks differ systematically, and what do these differences suggest about sex-specific cognitive strategies?

### WP 2: Going dynamic: Sex differences in time-resolved FC

WP 1 will provide insights into sex differences in the overall NV-AS induced by different movies, thus identifying sex differences in brain networks evoked over the temporally aggregated state of perceiving a complex situation. However, one of the main advantages of using movies in the study of individual differences is that their content varies dynamically and that due to the shared stimulus experienced by all participants the impact of the dynamic movie content on the brain can be directedly analysed. Making use of this, the present WP will further disentangle the temporally aggregated FC pattern of the NV-AS into time resolved FC patterns at each time point of the movie. Going beyond characterizing “state type” movie content as a whole, here the main aim is to directly identify specific events within the movies that result in distinct time-point specific FC patterns that differ between females and males. These, in turn, can be further analysed through the use of temporally resolved rather than movie wide annotations.

To achieve this goal, we will again parcellate the fMRI data based on an established parcellation (e.g. [40]) and compute a mean activation time course for each parcel. Instead of considering the NV-AS, we will now decompose static FC patterns into moment-by-moment, single repetition time (TR) co-fluctuation patterns [51, 52]. Basically, the Pearson correlation which is above used as a measure of temporally aggregated FC between pairs of brain regions [53] is “temporally unwrapped” by calculating the element-wise product of each pair of nodes’ z-scored time series. For each edge, i.e. connection between two brain parcels, this results in a time series - typically referred to as ‘edge time series’ (eTS) - representing the instantaneous co-fluctuation magnitude between the pairs, or simply speaking, the development of FC over time [52].

To identify dynamic FC differences between females and males during movie watching, we will identify time points within the movies, at which females’ and males’ FC patterns are most distinct. To do so, we will employ a ML approach at each time point to classify sex based on the individual time resolved FC patterns. Given that the dimensionality of these features, i.e. the number of edges, is extremely high, we will first employ a principal component analysis (PCA) for dimensionality reduction. Then, for each time point, the first n (e.g. 50) principal components will be used as features to train a sex classifier for which classification accuracy will be determined by use of a CV approach. Again, hormone levels and OC status will be included in the models as confounds to control for hormone related variability and possible confound leakage will be assessed and controlled for [41].

Using permutation tests we will identify those time points, for which classification accuracy differs significantly (p < 0.05) from chance, thus identifying events within each movie for which female and male time-resolved FC differs most. This approach offers the unique opportunity to link temporally specific sex differences in FC to movie content, thus identifying specific situations to which the sexes react differently. To characterize these situations, annotations within Ju-MOVIES-An will be used to identify movie events driving sex differences in time specific FC together with sex specific FC patterns driven by these features. To this aim, for each of the significantly different time points, the presence or absence of specific movie features (e.g. human bodies, faces, animals, scene cuts) will be coded binary, while continuous features (like luminance and audio level) will be coded as continuous numbers, thus creating a movie feature vector for each significant time point. We assume that typical sex differences in time resolved FC patterns will repeat across similar types of scenes in the different movies. Therefore, we will cluster the time points inducing significant differences between females and males according to their feature vectors, thus revealing parts of the movies that evoke sex difference during scenes with similar content. Then, for each of the time point clusters, we will compute a typical female and male FC pattern as the first component of a PCA across the FC patterns assigned to this cluster. This will identify typical female and male FC patterns in response to movies content associated with this cluster of movie scenes.

Finally, we will identify the pattern of brain regions that are most strongly involved in the typical female and male FC patterns for each cluster. Firstly, we will threshold the typical female and male FC patterns to identify most important edges in the sex-specific networks. Then, for each brain region, we will compute the weighted sum of all edges connected to that region and identify most important network nodes by selecting those for which summed FC strength exceeds the mean + 2 standard deviations across all nodes. This procedure will identify the sex specific spatial distribution of brain networks evoked by specific scenes in the movies.

Altogether, this procedure will shed light on which features within the movies induce most pronounced differences between females and males. Together with a set of features describing the movie scenes, we will identify female and male typical brain networks responding to these situations. While we expect to identify cognitive domains that match those identified in classical TB studies, the present approach will not only identify differences in specific isolated cognitive domains but reveal sex differences in cognitive strategies of dealing with certain complex situations. For example, while TB studies have identified sex differences in specific brain regions (like the fusiform face area) when participants viewed pictures of faces presented in isolation [54], our approach will depict sex differences in the brain when faces are encountered in a multimodal situation like in real life. Consideration of the brain networks evoked differently in females and males will shed light on sex specific neuronal patterns in perceiving faces.

Main Goal: Identify temporally specific movie events driving sex differences in the experience of real-life-like stimuli and related differences in time-resolved FC patterns.

Hypothesis 1 - Temporally Specific Sex Differences: Sex classification accuracy based on time-resolved FC will vary significantly across movie time points, reflecting temporally specific sex differences in FC.

Hypothesis 2 - Feature-Driven Divergence: Movie scenes containing social features (e.g., presence of faces, bodies, emotional content) will be associated with greater sex-related differences in FC.

Hypothesis 3 - Sex-Typical FC Patterns: Each movie feature cluster associated with sex differences will correspond to distinct and recurring male- and female-typical FC patterns, reflecting divergent neural strategies in processing complex, dynamic scenes.

Open Question - Relation to Classical Findings: How do naturalistic sex differences observed here relate to findings from traditional TB paradigms (e.g., isolated face viewing)? Are the same brain regions implicated, or do new networks emerge under ecologically valid conditions?

### *WP 3: Shared but unique: Examination of the sex specific shared response to dynamic emotions*

One of the main advantages of NV paradigms over the RS approach is that all participants are exposed to the same stimulus [55], resulting in a synchronization of the neural response across participants. However, at the same time, substantial individual differences within this response are preserved [39, 56]. In this WP, instead of looking at time resolved FC patterns, we will focus directly on the evolution of the neural response over time to examine in more detail, whether and how females’ and males’ brains differ in response to the dynamic movie content. Considering that sex differences in emotion perception and regulation have often been suggested in the literature (e.g. [57, 58]) and that movies are particularly effective in inducing strong negative and positive emotions [59, 60], we will focus on the sex differences in the brain’s reaction to the evolving emotional content over the course of the movies’ narratives. Results from this WP will extend existing findings on sex differences in emotion perception which have mostly only focused on single emotions in rather artificial situations.

To do so, we will employ the new analysis approach (TOPF, [24]) which has recently been developed in our lab. Simply speaking, for each brain region, this methodological approach extracts the shared brain response time course across a group of participants (through use of a PCA), which is evoked by watching the movie. Furthermore, the individual expression of this shared response is computed, which indicates to what extent the individual brain reaction matches the typical brain response across the group. In the present context, we will employ an adjusted “two group” version of TOPF. Instead of identifying the shared brain response across all participants, we will identify typical brain responses for females and males separately. Importantly, to control for hormone related variance within the data, we will regress each subject’s time series on their hormone levels and use the residuals, i.e. the part of the signal not explained by hormones, for computation of the shared response.

For each brain region we will compare the typical female and male response in two steps: Firstly, we will check whether the typical female response is significantly different from the typical male response. This will identify brain regions, in which the evoked brain response to movie differs fundamentally between females and males. To further explore whether depicted emotions are the driving factor in differential brain activation patterns in females and males we will employ the existing emotion annotation of our movies with respect to the six basic emotions. For each of the brain regions which display significantly different time courses for female and males, we will correlate the female and male time course with the emotion annotation to find out which emotions drive the differences. High correlation between the female respectively male shared response and annotation of specific emotions will identify emotions within the movies that drive sex differences in certain parts of the brain.

For brain regions, where the overall sex specific brain responses do not differ significantly, we will compare the individual expressions of this response by a two-sample t-test. This will identify brain regions, which react to the narrative of the movie in a similar way, but in which the intensity of the experience differs between females and males. We expect to find both types of regions mainly in higher cognitive regions, which we will further explore through the use of functional decoding [43].

Finally, we aim to find out whether, across the whole brain, females and males differ fundamentally in their perception of the evolving narrative of the movies. To this aim, for each subject, we will compute the similarity of individual brain response to the sex-specific typical response for each brain region. Then we will calculate a summary score (over all regions) to determine the sex of the subject by assigning them to the class with the higher overall similarity score. If this classification works with high accuracy, it can be taken to indicate, that there are typical female and male whole brain patterns in the perception of complex narratives. Should this not be the case it would speak to the brain patterns being driven by individual factors over sex.

Main Goal: Identify sex-specific patterns in neural responses to dynamic emotional content during NV, revealing how females and males process emotionally charged situations differentially.

Hypothesis 1 - Group-Level Differences in Shared Neural Responses: Typical brain responses to emotional NV content will differ significantly between females and males in brain regions associated with emotion processing, social cognition, and higher-order integration.

Hypothesis 2 - Emotion-Specific Divergence: Differences between female and male typical brain responses will be significantly associated with specific emotions (e.g., fear, sadness, joy).

Hypothesis 3 - Sex Classification Based on Whole-Brain Similarity: Whole-brain similarity to sex-specific typical responses will enable accurate classification of an individual’s sex, indicating the presence of distributed, sex-typical patterns in emotional narrative processing.

Open Question 1 - Which Brain Regions Show Fundamental Sex Differences? Which brain regions exhibit fundamentally different time-resolved responses to emotional content between females and males, and are these differences consistent across movie narratives?

Open Question 2 - Which Emotions Drive Neural Divergence? Are specific emotional categories (e.g., fear, anger, happiness) more likely to induce divergent neural responses between females and males?

#### Susanne Weis / Simon Eickhoff

SW will mainly handle the supervision of the two PhD students during all phases of the project, taking an active role in the design, implementation and testing of the workflows. She will also train the PhD students in fMRI data acquisition and analysis. SE will play a supervisory and advisory role during all phases of the project and participate in regular discussions of the workflows, results and interpretations. Both SW and SBE will also provide major input in the preparation of publications.

#### PhD students

PhD1 will focus on WPs 1 and 2, while PhD2 will focus on WPs 3 and 4. Since the initial data organization and preprocessing steps are comparable for all work package, the two PhDs will collaborate particularly closely during the initial phase of the project. Afterwards, they will work more independently on their respective WPs. Additionally, throughout the project, both PhDs will collect functional MRI data for the Ju-MOVIES dataset.

c) Requested budget (max. 2 A4 pages); please state in tabular form the expected costs for personnel, travel, and materials, indicating the overall budget.

Two PhD students (TVL 13, 65%) for 3 years, 2 x 3 x 81.600 x 0.65 = 318.240 Euro

PhD 1 will focus on WP1 and WP2, while PhD 2 will focus on WP3 and WP4, both using the existing Ju-MOVIE dataset. At the same time, both PhDs will be actively involved in collecting additional data for further extending the size of the dataset. Initially, both PhD students will work together in data preprocessing and quality control. After appropriate training by SW, both PhDs will implement methods, monitor the computations, consolidate and analyse the results and write articles for their respective WPs. While the specifics of the sub-projects differ, both PhDs will be able to work together and support each other.

Ideal PhD candidates will have a master’s degree in neuroscience, psychology, computer science or a related field with at least some programming experience in Python and R and preferably some experience with ML. The PhD students will work under direct supervision of SW while SBE will provide further guidance.

d) Declarations of intent may be attached to the application if applicable.

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