# On the same wavelength: The relationship between neural synchrony and cognitive ability during movie watching in late childhood and early adolescence

Lyons, KM[1], Ho, W[2]., Stevenson, RA[3-6], Owen, AM[3,4,6,7], & Stojanoski*, B[3-6,8]

[1] Department of Psychology, King's University College, London, ON
[2] Department of Medicine, University of Toronto, Toronto, ON
[3] Program in Neuroscience, University of Western Ontario, London, ON
[4] Brain and Mind Institute, University of Western Ontario, London, ON
[5] Department of Psychology, University of Western Ontario, London, ON
[6] Western Institute for Neuroscience, University of Western Ontario, London, ON
[7] Department of Physiology and Pharmacology, Western University, London ON
[8] Faculty of Social Science and Humanities, Ontario Tech University, Oshawa, ON

Corresponding author
Bobby Stojanoski
Email: bobby.stojanoski@ontariotechu.ca
Faculty of Social Science and Humanities
Ontario Tech University, Oshawa, Ontario, L1G 0C5, Canada

# Abstract

Development during late childhood and early adolescence is associated with vast improvements to thinking and reasoning abilities. Coinciding with developing cognitive abilities, the environments children navigate become more complex, with an expanding social circle giving rise to richer and more elaborate experiences. If cognitive development is associated with more complex experiences, do individual differences in cognitive abilities influence how children and adolescents experience their world? To address this question, we investigated the relationships between intersubject correlation (ISC) during movie watching and cognitive scores in children and adolescents (aged 7 -15, N = 309). Data for the current study was obtained from the Healthy Brain Biobank. As part of the Healthy Brain Biobank protocol, participants watched a 10-minute clip of *Despicable Me* while in the fMRI scanner. They also completed the Weschler Intelligent Scale for Children (WISC). We compared the degree to which participants brain activity synchronized to other participants brain activity during the movie, as measured by ISC, and investigated if scores on the WISC predicted this synchrony. We found adolescents (ages 11-15) with higher cognitive scores showed greater ISC during movie watching in brain networks associated with social processing and executive functions compared to those with below average cognitive scores. These networks included the frontoparietal and default mode networks. This pattern was not evident in children (ages 7-11) who differed in their cognitive scores. These results suggest that adolescents with more mature cognitive abilities may have more similar experiences of naturalistic stimuli. Our results also suggest that children may be less reliant on the frontoparietal network when processing movies, compared to previous findings in adults.



**Keywords:** Neural synchrony, brain development, fMRI, cognition, inter-subject brain synchrony

# Introduction

The period between late childhood and adolescence is marked by tremendous physical, social, and intellectual development. During this time, the brain undergoes widespread structural and functional changes in regions associated with high-level cognition, including the frontal and parietal cortices (Baker et al., 2015; Blakemore, 2012; Giedd et al., 1999; Sowell et al., 1999; Tamnes et al., 2017). These neural changes coincide with improvements in higher-level cognitive abilities, such as working memory, attention, and reasoning (Crone et al., 2004; Gur et al., 2012; Kwon et al., 2002; Luca et al., 2003; Luciana et al., 2005; Theodoraki et al., 2020). Cognitive development is unique for every child, such that these abilities improve at different rates for different children. This individual variation is predictive of many important outcomes, including academic success (Best et al., 2011; Morgan et al., 2019; Rohde & Thompson, 2007; Zaboski et al., 2018), health (Brown & Landgraf, 2010; Reimann et al., 2020; Stautz et al., 2016), and well-being (Nieto et al., 2020; Stern et al., 2017). Coinciding with developing cognitive abilities, the environments children navigate become more complex, with an expanding social circle giving rise to richer and more elaborate experiences (Zelazo, 2004). If cognitive development is associated with more complex experiences, do individual differences in cognitive abilities influence how children experience their world?

Investigating individual differences in how the world is experienced is a challenge, as many of the measures currently available do not reflect how children and adolescents process complex information within the real world. Naturalistic stimuli, such as movies, offer a potentially powerful way to characterize the relationship between individual differences in cognitive development and shared experiences. Movie watching parallels many real-world experiences; for instance, both require the integration of perceptual and cognitive systems to make sense of complex information that changes across time. When individuals watch the same movie, their brains become highly synchronized (as measured by inter-subject correlation, or ISC) with each other (Hasson, Landesman, et al., 2008). Previous work has shown that movies with a narrative lead to greater ISC across the entire brain compared to video clips without a plot (Hasson, Landesman, et al., 2008) and synchrony across participants is absent when they are at rest (Simony et al., 2016). The degree of ISC in adults is predictive of individual differences in emotional processing (Guo et al., 2015), theory of mind (Richardson et al., 2018), and memory

(Baldassano et al., 2017; Chen et al., 2017; Meshulam et al., 2021). Neural synchrony has also been used to assess conscious awareness in clinical populations (Laforge et al., 2020; Naci et al., 2014). These findings have led some to propose that neural synchrony is a measure of shared experiences, particularly when occuring in the frontoparietal and default mode networks (Naci et al., 2014; Nummenmaa et al., 2018; Zadbood et al., 2017).

The frontoparietal network, which is composed of regions in the lateral PFC and intraparietal sulcus, (Cui et al., 2020; Dosenbach et al., 2006; Marek & Dosenbach, 2018; Yeo et al., 2011), is associated with executive processes including working memory, cognitive flexibility, and reasoning (Burzynska et al., 2011; Peters et al., 2016; Satterthwaite et al., 2013; Wendelken et al., 2017), which are essential for plot following. Indeed, synchrony in the frontoparietal network is associated with the degree of suspense and the executive demands of the movie (Naci et al., 2014), and disappears during sedation (Naci et al., 2018). Similarly, the default mode network, which includes regions in the medial prefrontal cortex, posterior cingulate cortex, and inferior parietal cortices (Yeo et al., 2011; Yeshurun et al., 2021), is associated with cognitive processes involving task switching, autobiographical memory, theory of mind, and thinking about the future (Crittenden et al., 2015; Mars et al., 2012; Philippi et al., 2015; Smith et al., 2018; Xu et al., 2016; Yeshurun et al., 2021), all of which are also important for plot following. Regions within the default mode network show significantly more synchrony when participants are listening to an intact version of a story compared to a scrambled version (Simony et al., 2016), and greater ISC in this network is predictive of how well the movie is later interpreted (Yeshurun et al., 2017) and remembered (Chen et al., 2017; Nguyen et al., 2019, 2019; Zadbood et al., 2017).

Despite evidence for general changes in neural synchrony at a group level, there is considerable variability in how much people synchronize to each other while processing the same narrative, even when they have not been primed to interpret the story differently (Gruskin et al., 2020; Hasson & Honey, 2012; Lyons et al., 2020; Meshulam et al., 2021; Moraczewski et al., 2018). That is, some individuals show more synchrony, while others show less in response to the exact same stimuli. This suggests differences in synchrony are not due to the properties of the narrative or movie are or top-down instructions biasing how the plot is interpreted. Why some

people in a group synchronize more than others remains an outstanding question (Hasson & Honey, 2012).

One factor underlying variability in degree of synchrony may be cognitive functioning. Indeed, individuals who scored high on measures of social, emotional and cognitive abilities were more synchronized than individuals who scored lower on the same measures (Chamberlain et al., 2024) . Given the contributions of various cognitive processes required to follow the plot of a film, differences in cognitive abilities may impact the degree of neural synchrony between individuals watching the same movie. Indeed, this relationship may be stronger during specific stages of development. For instance, as children's cognitive abilities mature, those with more similar capacities may have more similar experiences of their environment. In support of this idea, Cantlon & Li (2013) found that the degree of synchrony between individual children to a group of adults in response to educational movie clips predicted academic abilities in each child.

However, there are only a few studies examining neural synchrony in children (Cantlon & Li, 2013; Chamberlain et al., 2024; Moraczewski et al., 2018) and most have focused on the degree to which a child's brain synchronizes with a group of adults processing the same narrative, a measure known as neural maturity. Although neural maturity has been found to correlate with brain development, social cognition, and academic scores (Cantlon & Li, 2013; Moraczewski et al., 2018; Richardson, 2019; Richardson et al., 2018), this may be a biased measure of shared processing. First, the abilities and preferences often differ qualitatively between children and adults (Carey, 1985; Chandler & Helm, 1984; Goldberg & Thompson-Schill, 2009; Gopnik et al., 2004; Jonauskaite et al., 2019; Luca et al., 2003; Salles et al., 2016), which likely influences how ones brain responds to complex narratives. Second, previous work has shown that children who have more 'adult-like' brains, thought to be due to accelerated development, are more likely to have experienced adverse childhood events and tend to have lower cognitive scores (Callaghan & Tottenham, 2016; Ellis et al., 2022; Shaw et al., 2006; Tooley et al., 2021). Therefore, calculating ISC between similarly aged participants may be a more appropriate measure of shared experiences during development, but whether synchrony between children and adolescents is related to cognitive abilities has yet to be investigated.

The current study investigated whether the degree of neural synchrony during movie watching in children aged 7 to 15 related to individual differences in cognitive performance, as measured by IQ. Specifically, a data-driven approach was used to examine if participants with different scores on the Weschler's Intelligence Scale for Children (WISC) differ in their degree of inter-subject correlations during movie watching. On the basis of the existing literature, it was predicted that participants with higher scores on the WISC would have greater neural synchrony in brain networks associated with plot following, including the frontoparietal network (Naci et al., 2014) and the default mode network (Chen et al., 2017; Nguyen et al., 2019, 2019; Zadbood et al., 2017).

# Methods

## Participants

Data was obtained from the Healthy Brain Biobank (HBN) database (described in detail in Alexander et al., 2017). The HBN is an on-going initiative to collect a large database of children and adolescents, between the ages of 5 to 21. The Chesapeake Institutional Review Board approved the study, and details on the HBN biobank can be found here: http://fcon_1000.projects.nitrc.org/indi/cmi_healthy_brain_network/. Secondary analysis of the HBN data was approved by the institutional research ethics board at Ontario Tech University. For the current study, participants were included if they were between the ages of 7 and 15 and both anatomical and movie fMRI data had been successfully acquired before the year 2020. Everyone included in the current study had written consent obtained from their legal guardians and written assent obtained from the participant. Participants were not excluded based on their handedness or if they had any diagnoses, including neurodevelopmental disorders, to ensure a sample that is representative of the whole population. All participants included in this study had completed the WISC (Wechsler, 2014), and were excluded if their full-scale IQ score was less than 70. Participants (N = 301) were also excluded because of failed registration, excessive motion, or if 25% or more of the data contained large 'spikes' (significant fluctuations in signal intensity).

Participants included in the final sample (N = 309, see Table 3.1 for participant demographics) were grouped into two age cohorts (Children and Adolescents) and four IQ bins

(Highest, Middle High, Middle Low, and Lowest). Figure 1 displays the distribution of ages and IQ scores. To assess the relationship between ISC and IQ within similarly aged children and adolescents, participants were split (using a median split of their ages) into two equal sized aged groups. Participants in the children group (N = 155) were below the age of 11.2 years, participants in the adolescent group (N = 154) were above the age of 11.2 years. The IQ bins were created using an inter-quartile split of the IQ data, creating a Lowest, Middle Low, Middle High, and Highest IQ group for each age cohort, which ensured equal sample sizes in each group. Based on a chi-square test of independence run separately for the age cohorts, the groups did not differ significantly in the number of participants with anxiety/mood disorders, autism, or ADHD (all uncorrected $p > .30$), except for the adolescent Middle High IQ group (N = 1) who had significantly fewer autistic participants compared to the adolescent Lowest IQ group (N = 11, $p = .005$). The Lowest IQ group in either age cohort did not statistically differ significantly from any other groups in the number of autistic participants (N ranged from 5 to 8). The Lowest IQ groups in both age cohorts had significantly more participants with specific learning disorders (N = 17 in both age cohorts) compared to the three other IQ groups ($p < .001$, N range from 5 to 9).

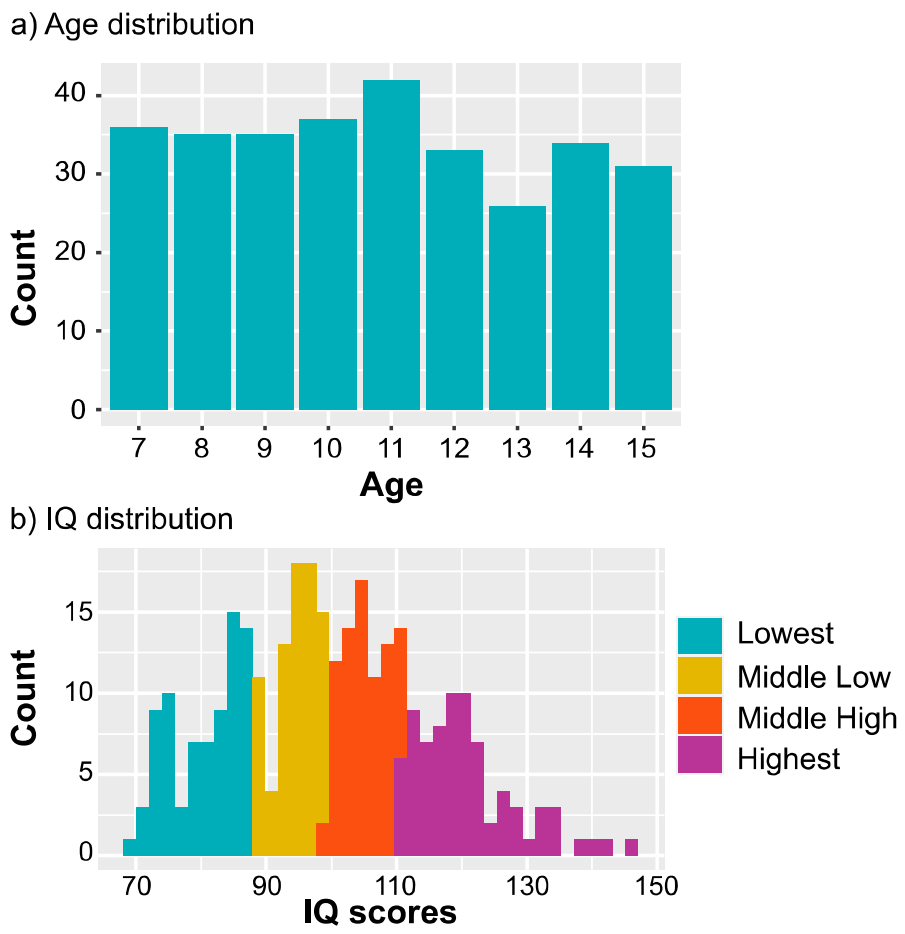
**Table 1**

*Summary of participant demographics.*

| | Group | N | Mean Age (SD) | Mean IQ (SD) | % Female |
|---|---|---|---|---|---|
| Children | Lowest IQ | 39 | 9.5 (1.3) | 81.8 (5.8) | 28.2% |
| | Middle Low IQ | 39 | 9.2 (1.3) | 96.5 (2.9) | 33.3% |
| | Middle High IQ | 39 | 9.2 (1.2) | 106.9 (2.8) | 46.2% |
| | Highest IQ | 38 | 8.9 (1.2) | 121.4 (8.0) | 47.4% |
| Adolescents | Lowest IQ | 39 | 13.7 (1.4) | 79.2 (4.5) | 33.3% |
| | Middle Low IQ | 39 | 13.2 (1.5) | 92.1 (3.6) | 30.8% |
| | Middle High IQ | 38 | 13.6 (1.3) | 103.1 (3.6) | 34.2% |
| | Highest IQ | 38 | 13.6 (1.3) | 120.5 (8.2) | 34.2% |

**Figure 1**

*Histograms displaying the distribution of a) age cohorts and b) IQ scores across the four groups.*



## (f)MRI Pre-processing

Functional and structural scans were co-registered and normalized to the Montreal Neurological Institute (MNI) template. Pre-processing of functional data included motion correction (using six motion parameters: left/right, anterior/posterior, superior/inferior, chin up/down, top of head left/right, nose left/right). Functional data were then spatially smoothed using a Gaussian filter (8 mm kernel), and low-frequency noise (e.g., drift) was removed by high-pass filtering with a threshold of 1/128 Hz. The data were denoised using Bandpass filter regressors, with cerebrospinal fluid, white matter signals, motion parameters, their lag-3 2$^{nd}$-order volterra expansion (Friston et al., 2000), and "spikes" (based on mean signal variance across volumes) as nuisance regressors.

## Exploratory whole brain inter-subject correlation analysis

The degree of inter-subject correlation across the whole brain was calculated using a leave-one-out approach, and this analysis was conducted separately for each group. That is, the pre-processed time course of every voxel was correlated (Pearson and then Fisher z-transformed) between each participant and the mean time course of every voxel from the rest of the group (N-1). A grey matter mask was used to extract r values within grey matter. One-sample t-tests were calculated on the resulting individual brain-wide correlation values. Multiple comparisons were corrected with a false discovery rate (FDR) of 0.05 to generate group maps of significantly correlated voxels.

## Network-based inter-subject correlation analysis

The degree of synchronization was computed within seven previously defined functional networks based on the Yeo et al. (2011) parcellation. Hypothesis driven analyses focused on the frontoparietal and default mode networks, however, five additional networks (Visual, Dorsal Attention, Ventral Attention, Somatomotor, Limbic) were included as exploratory analyses. The intra-group ISC for each of these seven networks was calculated using a leave-one-out approach. Specifically, the time course of each network (based on the average time course of each voxel within the network) for each participant was correlated with the average time course of each network for the remaining participants in the group, minus that participant (N-1). Finally, using the rstatix package in R (Kassambara, 2020), a mixed-model ANOVA was conducted to

determine if group membership was a significant predictor of intra-group synchronization across the two networks of interest, as well as the five exploratory networks. This was done separately for both age cohorts. The model included ISC values as the outcome variable and group (a between-subject factor) and network (a within-subject factor) as the predictor variables. The networks that showed a significant effect of group were followed up with Welch t-tests (all results were FDR corrected to 0.05).

### Cluster-based inter-subject correlation analysis

To ensure the method of grouping participants did not bias the results of the current study, pairwise correlations were calculated in the default mode and frontoparietal networks. This was done by calculating the mean time course (i.e. by averaging across all voxels) separately in both networks for each participant, and then correlating it with every other participant's mean time course. Finally, a k-means clustering analysis was conducted to determine whether groups of participants could be identified based solely on the degree of neural synchronization, and whether cluster-based group membership was associated with differences in cognitive abilities. The MATLAB function evalclusters was used to identify the optimal number of clusters based on the variance in the data using the Calinski-Harabasz Index, computed over 1000 iterations to minimize the fitting parameter. Based on the groupings generated from this cluster analysis, a logistic regression analysis was computed to investigate which factors, if any, (i.e. age, full scale IQ, and scores on the five subscales of the WISC) significantly predicted the cluster-generated groupings.

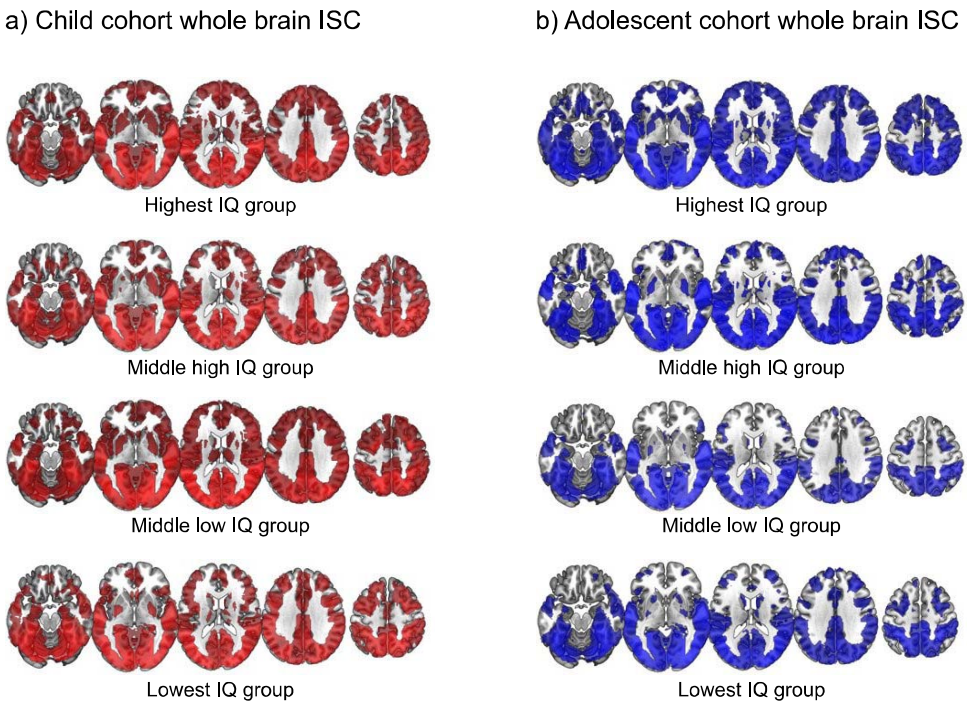
## Results

### Whole brain ISC

All age cohorts (Child and Adolescent) and IQ groups (Highest, Middle High, Middle Low, Lowest) showed significant synchrony across the entire cortex (see Figure 3.2), including much of the visual and auditory cortex, as well as associative regions of the brain.

**Figure 2**

*Whole brain spatial maps with significant intra-group ISC displayed for (a) the child and (b) adolescent cohorts.*




*Note:* All age cohorts and IQ groups had significant synchrony in sensory and associative regions of the brain (FDE corrected $p < .05$).

## Network based ISC

A mixed effects ANOVA was conducted on both age cohorts separately. ISC values were normally distributed (assessed using Shapiro's test, p-values ranged from .17 to .72), except in the dorsal attention network for the child cohort ($p = .007$) and adolescent cohort ($p = .04$), and in the limbic network for the adolescent cohort ($p = .025$). There were no significant deviations in the assumption of equal variances in ISC values across groups (assessed using Levene's test,

p-values ranged from .12 to .99). The Greenhouse-Geisser sphericity correction was applied to correct for violations in sphericity. In the child cohort, there was no main effect of group ($F_{(3, 151)} = 1.6$, $p = .19$), but there was a main effect of network ($F_{(4.4, 660.8)} = 181.3$, $p < .001$) and a significant interaction between group and network ($F_{(13.1, 660.8)} = 1.9$, $p = .02$). This significant interaction suggested that the pattern of group differences in ISC values differed across the seven networks. When each network was investigated separately, only the somatomotor network showed a significant group effect ($F_{(3,151)} = 5.7$, $p_{adj} = .007$, see Table 3.2). Post-hoc comparisons indicated that children in the Lowest IQ group had significantly less ISC compared to the Middle Low ($t_{(74.5)} = 2.94$, $p = .009$), Middle High ($t_{(69.0)} = 3.21$, $p = .006$) and Highest IQ group ($t_{(63.8)} = 3.90$, $p = .001$).

The adolescent cohort showed a main effect of group ($F_{(3, 150)} = 5.0$, $p = .002$), a main effect of network ($F_{(3.8, 575.9)} = 144.5$, $p < .001$), but no significant interaction between group and network ($F_{(11.5, 572.9)} = 1.3$, $p = .22$). These results suggested that the groups differed significantly in their degree of ISC, but that the pattern of group differences was not significantly different across the seven networks. When each network was investigated separately, all but the dorsal attention and limbic networks showed a significant group effect (see Table 2 for the statistics for each network). Post-hoc comparisons indicated that for the networks that showed a significant group effect, the Highest IQ group had greater ISC compared to the Lowest and Middle Low IQ groups, although some of these differences failed to reach significance after multiple comparison correction (uncorrected p values ranged from .019 to < .001, corrected p values ranged from .056 to .001, see Figure 3.3)

**Table 2**

*Results from separate ANOVAs calculated to compare ISC in the four IQ groups across the seven networks.*

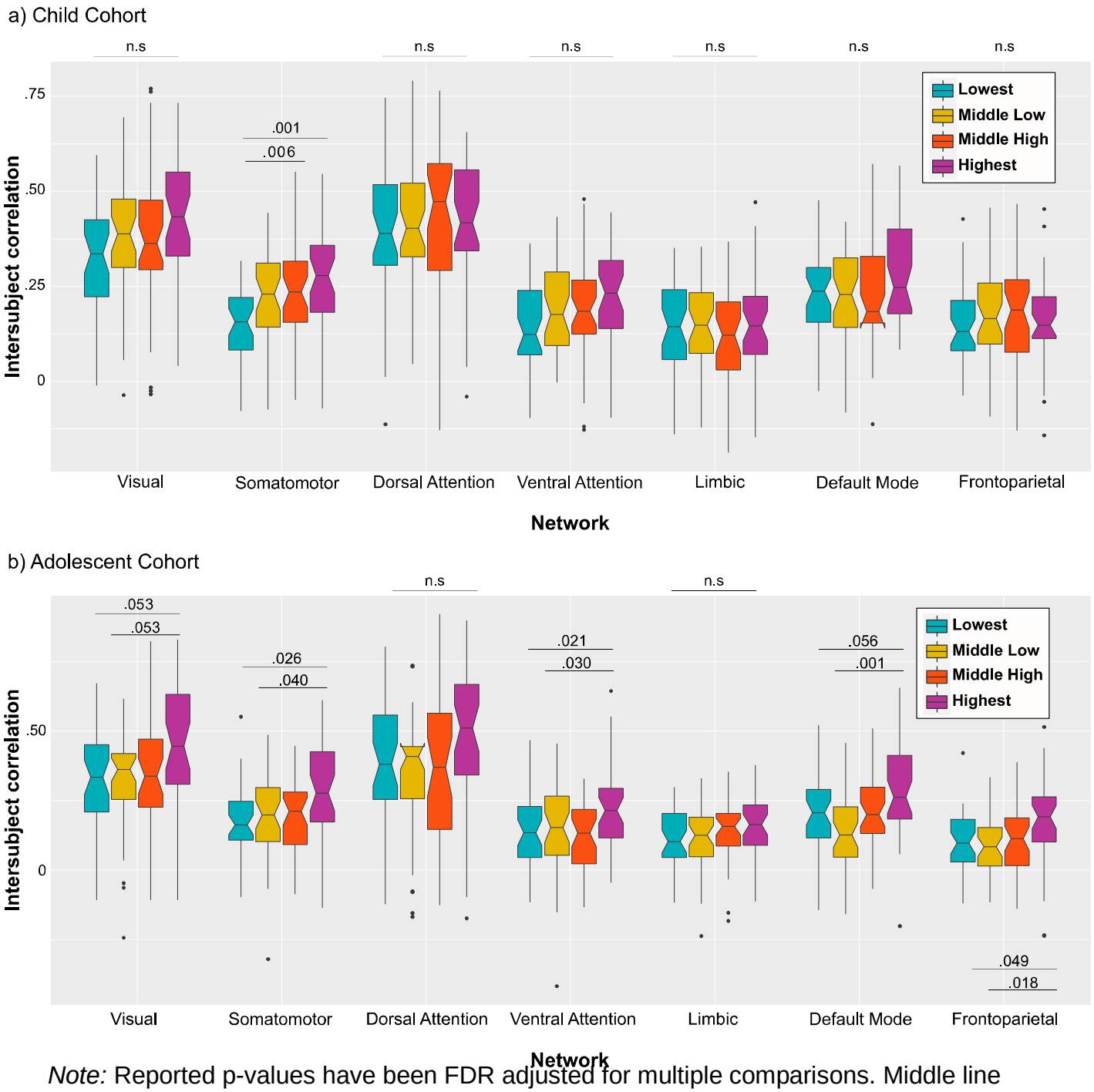
| | Network | df | F | p | $p_{adj}$ | Generalized $Eta^2$ |
|---|---|---|---|---|---|---|
| Child | Visual | 3, 151 | 2.62 | 0.053 | 0.186 | 0.049 |
| | Somatomotor | 3, 151 | 5.69 | 0.001 | 0.007* | 0.102 |
| | Dorsal Attention | 3, 151 | 0.13 | 0.943 | 0.943 | 0.003 |
| | Ventral Attention | 3, 151 | 2.10 | 0.103 | 0.189 | 0.040 |
| | Limbic | 3, 151 | 0.17 | 0.916 | 0.943 | 0.003 |
| | Default mode | 3, 151 | 2.06 | 0.108 | 0.189 | 0.039 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Frontoparietal | 3, 151 | 0.46 | 0.709 | 0.943 | 0.009 |
| Adolescent | Visual | 3, 150 | 3.13 | 0.028 | 0.039* | 0.059 |
| | Somatomotor | 3, 150 | 3.69 | 0.013 | 0.023* | 0.069 |
| | Dorsal Attention | 3, 150 | 2.62 | 0.053 | 0.062 | 0.050 |
| | Ventral Attention | 3, 150 | 4.98 | 0.003 | 0.011* | 0.091 |
| | Limbic | 3, 150 | 1.01 | 0.392 | 0.392 | 0.020 |
| | Default mode | 3, 150 | 5.95 | 0.001 | 0.005* | 0.106 |
| | Frontoparietal | 3, 150 | 4.37 | 0.006 | 0.014* | 0.080 |

*Note:* Uncorrected p-values displayed as p, FDR corrected p-values displayed as $p_{adj}$.

**Figure 3**

Boxplots displaying ISC for each IQ group across every network for the child cohort (displayed in panel a) and the adolescent cohort (displayed in panel b).




*Note:* Reported p-values have been FDR adjusted for multiple comparisons. Middle line represents the median ISC value for each group. The color boxes indicate the interquartile range for each group. Dots indicate outlier ISC values.

## Cluster-based inter-subject correlation analysis

To assess the robustness of the intra-group ISC analysis, pairwise inter-subject correlations were calculated between each participant and every other participant in the default mode and frontoparietal network (see Figure 3.4). A k-means clustering analysis indicated that the data best clustered into two groups for both networks: one group with high pairwise correlations and a group with low pairwise correlations (see Table 3.3 for participant demographics of each group). An exploratory logistic regression analysis indicated that cluster membership in the default mode network was significantly predicted by IQ scores (p = .041), and scores on the visual spatial (p = .025), verbal comprehension (p = .036), and working memory (p = .038) subscales of the WISC. Specifically, those with higher scores were more likely to be part of the high similarity cluster. Age was not a significant predictor of cluster membership in the default mode network. The results of a logistic regression analysis also indicated that cluster membership in the frontoparietal network was significantly predicted by age (p = .006), with participants in the high similarity group being slightly younger than participants in the low similarity group. However, cluster membership in the frontoparietal network was not predicted by full scale IQ or any of the WISC subscale scores.

**Figure 4**

*Pairwise correlation matrices across all subjects from all age and IQ groups for the default mode and frontoparietal networks.*

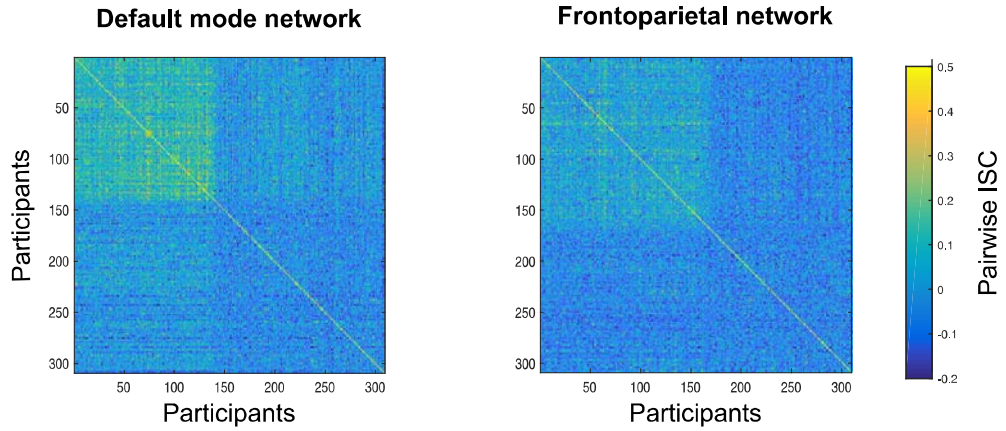


**Table 3**

*Mean age and WISC scores for the high similarity and low similarity clusters for the default mode and frontoparietal networks.*

| Group | *Default mode* | | *Frontoparietal* | |
|---|---|---|---|---|
| | High Similarity | Low Similarity | High Similarity | Low Similarity |
| *N* | 138 | 171 | 168 | 141 |
| *Mean Age (SD)* | 11.2 (2.4) | 11.4 (2.6) | 11.0 (2.5) * | 11.8 (2.5) * |
| *Mean IQ (SD)* | 102 (16) * | 98 (15) * | 101 (16) | 99 (16) |
| *Mean WMI (SD)* | 100 (14) | 96 (15) | 98 (14) | 98 (16) |
| *Mean VSI (SD)* | 104 (17) | 99 (16) | 102 (17) | 100 (16) |
| *Mean VCI (SD)* | 106 (15) | 102 (15) | 105 (15) | 102 (15) |
| *Mean FRI (SD)* | 103 (15) | 100 (16) | 102 (16) | 100 (15) |
| *Mean PSI (SD)* | 96 (15) | 95 (15) | 96 (15) | 95 (15) |

*Note:* WMI = Working memory index, VSI = Visuospatial index, VCI = Verbal comprehension index, FRI = Fluid reasoning index, PCI = Processing speed index.

# Discussion

The current study found that adolescents (between the ages of 11 and 15) with higher IQ scores showed greater neural synchrony, as measured by inter-subject correlation, compared to those with lower IQ scores. Interestingly, several of the brain regions that showed this pattern, including the frontoparietal and default mode networks, have previously been found to be associated with following the plot of a movie. For instance, synchrony in the frontoparietal and default mode networks is modulated based on whether adult participants had more similar (increased) or different (reduced) interpretations (Nguyen et al., 2019), and understanding (Yeshurun et al., 2017) of the narrative of the movie. Additionally, Naci et al. (2014) found that synchrony in the frontoparietal network was associated with the executive load of a movie; that is, time points during movies that are the most engaging were also the periods that show the greatest synchrony in this network. Based on this work in adults, the current study's findings suggest adolescents with higher cognitive scores likely had a more similar experience of the movie compared to those with lower IQs.

However, differences in the degree of neural synchrony between groups of adolescents based on IQ scores were not specific to the default mode and frontoparietal networks. Individuals in the Highest IQ group had significantly greater synchrony in the visual, somatomotor, and ventral attention networks compared to the groups with lower scores. Although synchrony in sensory areas has been shown to occur in the absence of plot following (Hasson et al., 2004; Hasson, Landesman, et al., 2008; Honey et al., 2012; Lerner et al., 2011; Naci et al., 2014), there is evidence that synchrony in sensory areas may be associated with plot following. For instance, several studies have found that individual differences in neural synchrony in the premotor cortex, sensorimotor cortices, and frontal eye fields is predictive of comprehension and memory of the narrative being processed (Meshulam et al., 2021; Yeshurun et al., 2017). These results give rise to an interesting question about individual differences in the relationship between sensory processing and higher-level cognition during movie watching: Do differences in high-level cognition influence lower-level sensory processing during naturalistic stimuli, or do sensory processes form the necessary foundation on which high-level cognitive abilities are built? Addressing this question from a longitudinal perspective will shed light on the neural mechanisms underlying the association between cognitive development and shared experiences.

In contrast to the study's hypothesis, the pattern observed between adolescents' IQ scores and neural synchrony in the default mode and frontoparietal networks was not evident in children between the ages of 7 and 11. The only differences in neural synchrony between children in this cohort with across groups based on IQ was primarily in the somatomotor network. There are several potential reasons for why the current study failed to find evidence for the hypothesized differences in children. One reason might be that children rely less on high-level cognitive processes when watching movies. However, this explanation seems unlikely because we found significant synchrony across the entire cortex for all four IQ groups in this age cohort. This suggests that they were paying attention to and processing the plot of the movie. Moreover, the movie in the study, *Despicable Me*, is a popular movie for children in this age range, and is in fact, part of the highest grossing animated film franchise ever (Jesus, 2017). Another potential explanation for these null results is the asynchronous development of different regions in the brain. It has been proposed that during childhood and adolescence the brain develops along a sensorimotor-association cortical axis (Sydnor et al., 2021, 2023), and children are relying on sensorimotor regions to process the movies to compensate for underdeveloped association

cortices, including fronto-parietal regions (Dong et al., 2021). Relatedly, the parcellation (based on the Yeo et al. (2011) spatial maps) used in this study may not accurately capture functional networks in children. This is particularly relevant for the default mode and frontoparietal networks which undergo considerable change throughout childhood and adolescence, and the adult-based parcellated spatial maps may not completely capture how those networks are parcellated in children (Dong et al., 2021). Consequently, our results may reflect an underrepresentation of the degree to which children's brains were synchronized during movie-watching. Alternatively, perhaps the current study did not find that IQ was predictive of neural synchrony in children because the method used to group participants may have masked potential differences. The groups were divided arbitrarily based on an inter-quartile/median split, but IQ scores and age are continuous in nature. It is possible that this was not the best way to investigate the relationship between IQ and ISC.

To explore the robustness of the association between IQ scores and neural synchrony, pairwise correlations were calculated across all subjects. This analysis revealed that the data best fit a model with two clusters in both networks: a cluster of high similarity, and a cluster of low similarity. The results of an exploratory logistic regression analysis in the default mode network were consistent with the findings from the IQ grouping analysis in adolescents; participants with more similar time courses were more likely to have higher scores on the WISC (on average, approximately 4 IQ points higher), and on the working memory, verbal, and visuospatial subscales. The two default mode clustering groups did not differ significantly in their age. These results suggest that IQ scores are predictive of synchrony in the default mode network, regardless of the age of participants. Specifically, participants with lower IQ scores, as well as verbal, visuospatial, and working memory abilities, have more idiosyncratic neural responses to a movie compared to those with higher IQs.

Previous work has consistently shown that synchrony in the default mode network is dependent on how someone is engaging with and understanding a movie plot (Ames et al., 2015; Chen et al., 2017; Hasson, Landesman, et al., 2008; Hasson, Yang, et al., 2008; Lerner et al., 2011; Nguyen et al., 2019; Yeshurun et al., 2017). Our findings within the default mode network support the idea that adolescents, and perhaps children who have more matured cognitive abilities, process the movie in a more similar fashion. Higher cognitive abilities may help

participants stitch together different nuances in the plot, which may lead to understanding the movie in a more comparable way. It is plausible that having better working memory, verbal, and visuospatial abilities would make following a movie plot less effortful.

The clustering analysis in the frontoparietal network revealed that IQ scores were not predictive of clustering group in this network. These results are in contrast with our other findings that adolescents with the highest IQ group had greater synchrony in the frontoparietal network compared to those with lower scores. One possibility for this conflicting result could be that this effect was subtle in the adolescent group, and therefore was lost when younger participants were included in the analysis.

Conversely, the logistic regression revealed that age was a significant predictor of clustering group in the frontoparietal network. Those in the high similarity cluster were slightly younger, on average by 10 months, than those in the low similarity group. The current sample was skewed towards a slightly younger group (see Figure 1), which may explain why the high similarity cluster in the frontoparietal network contained more younger participants, likely reflecting that idea that similar aged children experienced the movie in a more similar way. However, this is not the case for all older participants as the high similarity cluster included 15-year-old participants, the oldest age cohort included in this study, suggesting that shared experiences of the movie are not constrained by age. That said, *Despicable Me* was released in the year 2010, so another potential factor contributing to higher synchrony in younger children is that they are less likely to have seen this movie compared to adolescents, although this information was not available. There is evidence that familiarity with a stimulus leads to a decrease in neural synchrony (Aly et al., 2018; Dmochowski et al., 2012; Sternin et al., 2023). Future studies should investigate how neural synchrony changes across development in a longitudinal design, which would be the best way to disentangle cohort effects from developmental changes.

The current study's sample was highly heterogeneous; participants were not excluded for their handedness or having a DSM diagnosis, and the range in IQ scores was approximately 70 points. Despite this heterogeneity, only two clusters emerged from the pairwise correlations in both networks of interest. Participants in the high similarity cluster had similar patterns of brain

activation while watching a movie, whereas those in the low similarity cluster had unique patterns of activation. Although participants in the high similarity cluster in the default mode network were, on average, 4 IQ points higher than the low similarity cluster, the range of IQ scores were nearly identical. Moreover, the age range was also nearly identical (approximately 7 to 15 for both groups). This suggests that in addition to IQ being a significant predictor of neural synchrony in the default mode network, there are other factors that likely predict whether children and adolescents have unique versus similar patterns of brain activation during movie watching. For instance, what explains why a 7-year-old child with an average IQ shows a high degree of similarity in brain activity in the default mode network to a 15-year-old adolescent with a high IQ? Why do two 10-year-old children with similar IQ scores show distinct activation patterns in the default mode network (as is seen in the low similarity cluster)? Future studies should investigate whether these clustering differences are associated with a different interpretation of the naturalistic stimuli. A limitation of the current study is that comprehension data for the movie *Despicable Me* was not collected for the sample used in the current study.

*Conclusion*

Overall, the current study found that adolescents with higher IQ scores show greater neural synchrony when watching a movie, compared to those with lower scores. These results suggest adolescents with more mature cognitive abilities may have more similar experiences of naturalistic stimuli. Interestingly, we did not find this pattern children when participants were grouped by age. Contrary to our hypotheses, we found differences in neural synchrony appeared most prominently within the default mode network but were not reliably found within the frontoparietal network, which may suggest children are less reliant on the prefrontal cortex, and instead rely on the cognitive systems subserved by the default mode network to process movie.

To expand on our results, future studies should also expand on how cognitive abilities are quantified. Although IQ scores are often treated as a proxy for general cognitive ability, they are also thought to be biased towards certain groups and influenced by socioeconomic factors (Brinch & Galloway, 2012; Capron & Duyme, 1989; Hanscombe et al., 2012; Marks, 2010; Zoref & Williams, 1980). For instance, differences in access to education, home environment, and adverse life events influence a child's performance on IQ tests (Brinch & Galloway, 2012; Capron & Duyme, 1989; Clearfield & Niman, 2012; Hanscombe et al., 2012; Kira et al., 2012;

Ritchie et al., 2013; Ronfani et al., 2015; Saltzman et al., 2006; van Os et al., 2017). In addition, future studies should include objective measures of movie comprehension to link with neural synchrony and cognition. If synchrony in the default mode network is critical to have a similar experience of the movie, including a comprehension measure may explain why some children and adolescents showed a high degree of synchrony in the default mode network, whereas others did not, even among participants with similar ages and cognitive scores.

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