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A META-ANALYSIS OF THE NEURAL MECHANISMS UNDERLYING DECISION-MAKING PROCESSES IN ADOLESCENTS IN RISKY SITUATIONS

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ABSTRACT

Adolescence is widely recognized as a critical developmental period, marked by significant psychological and neurocognitive changes. Neurocognitive developments, particularly in the prefrontal cortex, facilitate higher-order cognitive abilities and undergo rapid growth during this period. Understanding adolescent decision-making processes is crucial for several reasons. It provides insights into their unique developmental challenges and informs the design of interventions to mitigate risky behaviors affecting both individuals and the larger community. This meta-analysis investigates the neural mechanisms underlying adolescent risky-situation decision-making and finds commonalities, differences, and limitations in current research. Key insights include the common findings of activation in the middle frontal gyrus, ACC, and temporal regions.

KEYWORDS: Adolescence, Risky Behaviors, Decision-Making Processes, Neural Mechanisms, Peer Influence

INTRODUCTION

It is well known that adolescence is considered a critical developmental period, for many reasons. First, the psychological aspect must be considered. There is a heightened potential to shape the long-term functioning of affective circuitry from about ages 10 to 19 (Gerhard et al., 2021). This means that they experience increased sensitivity to social interactions and peer acceptance, which may influence key factors in their development, such as self-esteem and social behavior. Second, we must consider the neurocognitive developments during the adolescent period. Significant changes are known to occur in brain regions involved in decision-making, such as the prefrontal cortex. Further, higher-order cognitive abilities and the various brain regions that facilitate them undergo rapid changes and growth (Ravindranath et al., 2024).

It is also vital to consider the importance of understanding adolescents' decision-making processes. First, comprehending these processes provides insight into their unique developmental stages and challenges (Fischhoff et al., 1999). For example, a study with adolescent girls revealed that they often saw only one either-or choice rather than a series of options in tough decisions (Beyth-Marom & Fischoff, 1997). Moreover, as a large proportion of our population, adolescents are known to engage in riskier behaviors, and studying their decision-making helps design interventions to mitigate such risks, which may affect both them and the larger community. Cognizance of their decision-making strategies can lead to improved educational blueprints, pointing to improved life outcomes and performance.

Most importantly, adolescence is marked by key differences in decision-making, namely the ability to weigh outcomes outside of one's direct experience, reactivity to potential rewards, tolerance for uncertainty, and the ability to assess the value of an outcome and the risks associated with it (Hartley & Somerville, 2015). For one, current research supports that adolescents typically have poorer working memory, which is related to a decreased ability to suppress short-term desires, e.g., early sexual activity or drug use (Maslowsky et al., 2019). Continuing neuroimaging studies reveal a heightened reward drive during adolescence, which may explain why some are more inclined to take risks than others. This may further provide insight into why they typically show more inclination to risk-taking than adults (Crone & van Duijvenvoorde, 2021).

Research Question

This meta-analysis aims to study the question: What are the neural mechanisms underlying decision-making processes in adolescents in risky situations? To do so, it studies many key aspects, which will be further detailed.

1. Adolescent Sensitivity to Peer Influence
2. Risk-Taking and Reward Processing
3. Cognitive Flexibility and Decision-Making
4. Sensitivity to Social Evaluation
5. Media Use and Brain Development

Research Scholars Program, Harvard Student Agencies, In collaboration with Learn with Leaders

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Significance

Studying the neural mechanisms of adolescent decision-making, especially in risky situations, has many practical applications in several fields. Using the current understanding of neuroscientific research, educators can potentiate their teaching by aligning with biological knowledge, which may improve outcomes. Some believe that key methods from medicine can be applied to educational science; similar to how discoveries from labs are tested with animals, then a few humans, then larger numbers of people, educational practices could behave comparably and may yield a plethora of minor advances that add up (Ravindranath et al., 2024). However, there are major criticisms of this field of thought. For one, education is a social phenomenon, and reducing it to neural mechanisms is not an adequate solution for the social nature of the environment. Moreover, the complex, timely, and expensive manner of collecting neuroscience data discourages interdisciplinary discussion with cognitive science (Thomas et al., 2018).

Neuroscientific literacy with adolescents can also guide policymakers in creating evidence-based policies that support health and cognitive ability. While current research on socioeconomic status's relationship with the brain is relatively new, its implications may be highly beneficial and worthwhile. Disparities in cognitive and emotional function vary between individuals, and there is rigorous research into linkages between socioeconomic status, the brain, and vulnerability to physical illnesses. Collaboration between the fields of policy and adolescent neuroscience could greatly aid in tackling issues of poverty and economic injustice (Farah, 2018, pp. 2, 3, 17).

Finally, identifying the neural mechanisms involved in adolescent decision-making can lead to better-targeted mental health interventions, promoting better mental health and well-being. Current research has led psychiatrists and public health experts to develop novel techniques for preventive interventions that encompass different settings and levels of prevention. It has largely increased the accessibility and acceptability of such interventions, most notably in a non-stigmatizing and tailored manner. Additionally, research has suggested that new literature-based interventions like internet-based interventions and new therapies have proven effective for mental health promotion and prevention (Singh et al., 2022).

Theoretical Background

It is important to first understand the neural basis of development during the adolescent period. One study used the BART (balloon analog risk task) experiment to examine regions of brain activation when faced with the decision of a risky choice that may or may not backfire but has a greater reward, or a risk-averse choice that guarantees a lesser reward. When using fMRI, they found significant neural activation in regions including the VS (ventral striatum), ACC (anterior cingulate cortex), thalamus, and cerebellum. In the same study, they imaged brain activation that covaried with stake size, called a stake-modulated contrast. They found that the bilateral insula, ACC, rMFG, and thalamus were the most stimulated, with the medial prefrontal cortex being deactivated. In the same study, it was found that these four brain regions were also marginally associated with greater risk in driving behavior (Pei et al., 2020).

Another study involving risk vs. ambiguity decisions showed a broad network of activation of frontal and prefrontal structures. This includes the right dorsolateral prefrontal cortex (DLPFC) extending to the precentral gyrus, left DLPFC, right ACC, bilateral orbitofrontal cortex (OFC), right inferior, and medial and superior frontal gyrus. They also found activation in temporal and parietal structures, specifically the temporal-parietal junction (TPJ) bilaterally, the bilateral middle temporal gyrus (MTG), the bilateral precuneus, and the inferior parietal lobe. The right insula and the right precentral gyrus were also activated. In the same study, when dangerous vs. safe options were given in a risky situation, there were two clusters of activation involving the left ACC, one cluster involving the right ACC, and one cluster involving the left superior temporal pole (TP) (Rodrigo et al., 2014).

A third study using the IAT (Implicit Association Test) with intertemporal decision-making showed activation of the orbitofrontal cortex, dorsolateral prefrontal cortex, and the FC in between. Further, the delay discount rate was negatively correlated with activation in the orbitofrontal cortex and left dlPFC and FC from the left dlPFC to the right dlPFC. Using the IAT with risky decision-making showed activation in the FC from the bilateral dorsolateral prefrontal cortex to the orbitofrontal cortex and the FC from the left dorsolateral prefrontal cortex to the right dorsolateral prefrontal cortex. The risk selection ratio is negatively correlated to activation in the orbitofrontal cortex and FC from the left dorsolateral prefrontal cortex to the right dorsolateral prefrontal cortex and orbitofrontal cortex.

Using the stoplight task, a fourth study measured increasing activation levels in the left lateral prefrontal cortex in adult participants compared with younger participants. They also found that when faced with peer pressure, adolescents' ventral striatum and orbitofrontal cortex experienced much higher levels of activation compared to both isolated decision-making and the decision-making of young adults and adults, showing that these two brain regions may be involved in adolescent risky decision-making. Significantly higher ventral striatum and orbitofrontal cortex activation was associated with risky decision-making among adolescents.

METHODOLOGY

Due to the simplistic nature of this meta-analysis, the selected literature for data compilation and analysis is relatively straightforward. Using multiple databases such as PubMed, Scopus, PsycINFO, etc., I selected 3 studies to compare. I used the search terms: "adolescent decision-making", "neural mechanisms", "risky situations", "fMRI", and "peer influence". The criteria for inclusion were studies involving adolescents, a focus on neural mechanisms, the use of fMRI neuroimaging techniques, and an examination of risky decision-making. The exclusion criteria were non-human studies, studies not using fMRI, and studies not focused on neural mechanisms. The 4 selected studies were either neuroimaging studies or behavioral

neuroscience studies, each peer-reviewed article with empirical data, and detailed methodology sections. They are detailed in Table 1 below.

Table 1			
Authors	**Method**	**data type**	**N**
Chein et al.	Stoplight task	fMRI data	40
Pei et al.	Balloon analog risk task; simulated driving task	fMRI data	83
Rodrigo et al.	Social Context Decision Task	fMRI data	60

RESULTS

Data Synthesis and Analysis

Using an FWE level of 0.05, Chein measured adults with statistically significant increased brain activation in all of the following areas: L Middle Frontal, L Inferior Parietal, L Middle Frontal (LPFC), L Middle Temporal, L Middle Frontal, and L Fusiform. In social settings compared to independent settings, there was statistically significantly more activation at the L Cuneus/Sup. Occipital. Inversely, there was less activation at: Precuneus, L Superior Frontal, Cingulate, R Middle Temporal. See Table 2.

Table 2: Regions showing significant (FWE < .05) main and interactive effects of age and social condition in association with Stoplight Task decision-making					
Region	BA	x	y	z	mm3
Main Effect of Age					
Adults > Adols.					
L Middle Frontal	6	−31	5	56	1404
L Inferior Parietal	40	−52	−37	41	243
L Middle Frontal (LPFC)	46	−46	11	26	540
L Middle Temporal	19	−53	−62	15	972
L Middle Frontal	10	−25	56	8	351
L Fusiform	37	−52	−55	−19	540
n.s. for all other pair-wise contrasts					
Main Effect of Social Context					
Peer > Alone					
L Cuneus/Sup. Occipital	19	−22	−82	32	297
Alone > Peer					
Precuneus	7	−2	−58	32	891
L Superior Frontal	9/8	−10	53	38	540
Cingulate	24/23	−1	−22	35	351
R Middle Temporal	21/38	59	8	−16	189
Interaction of Age × Social Context					
Ventral Striatum (VS)		9	12	−8	297
Mid. Orbitofrontal (OFC)	11	−22	47	−10	459
Note: Table from Chein et al. (Table 1)					

Similarly, at an FWE level of 0.05, Pei et al. measured adults with statistically significant increased brain activation in all of the following areas: L/R thalamus, R insula, L insula, R middle frontal gyrus, and L/R anterior cingulate cortex. Inversely, there was less activation at: Ventromedial prefrontal cortex, L middle temporal lobe, R temporal lobe, R cerebellum posterior lobe. See Table 3.

Table 3: Brain activations associated with the parametric level of the decision stake associated with the balloon. Peak MNI coordinates					
Brain region	x	y	z	t	k
Positive clusters					
L/R thalamus	-2.4	-26.1	1	6.13	82
R insula	35.4	18.6	-8	8.70	394
L insula	-36.8	18.6	-5	7.38	139
R middle frontal gyrus	25.1	53	22	6.41	94
L/R anterior cingulate cortex	4.5	35.8	22	7.29	171
Negative clusters					
Ventromedial prefrontal cortex	-9.3	42.69	-17	-7.58	254
L middle temporal lobe	-64.3	-12.3	-17	-6.81	123
R temporal lobe	62.9	-5.4	-5	-6.68	85
R cerebellum posterior lobe	21.7	-91.4	-29	-6.02	100
Note: Table from Pei et al. (Table 2)					

Finally, at an FWE level of $p \leq 0.001$, Rodrigo measured participants with statistically significant increased brain activation in the areas shown in Table 4.

Table 4: Significant clusters of activation in the whole-brain analysis for the contrast Risk > Ambiguity for all participants (N = 60) and by age and gender groups					
Region	BA	Cluster size	Z-score	x, y, z	mm3
Right temporoparietal junction	37	175	7.66	53, -60, 22	1404
Left temporoparietal junction	21	199	7.66	-56, -56, 22	243
Left inferior parietal lobe	40	22	6.40	-56, -51, 44	540
Right middle temporal gyrus	21	121	7.47	53, 1, -23	972
Left middle temporal gyrus	21	57	7.06	-56, -45, 1	351
Right inferior frontal gyrus, triangularis	45	45	5.83	53, 23, 16	540
Right inferior frontal gyrus, orbital	38	63	6.67	42, 23, -14	297
Left inferior frontal gyrus, orbital	38	14	6.10	-49, 19, -6	891
Right middle frontal gyrus	44	28	5.89	46, 23, 37	540

Left middle frontal gyrus	44	16	5.90	-37, 23, 37	351
Right precentral gyrus	6	67	6.67	46, 8, 46	189
Right superior frontal gyrus	8	15	6.04	23, 23, 46	297
Right insula	48	13	6.67	36, 16, -9	891
Right precuneus	23	212	6.97	12, -52, 34	540
Left precuneus	23	63	6.75	-4, -52, 35	351
Right dorsomedial prefrontal cortex	9	57	6.79	5, 38, 43	189
Right anterior cingulate cortex	32	12	6.79	7, 44, 23	459
Note: Table from Rodrigo et al. (Table 1)					

Overall, all three studies emphasize the critical role of peer influence on adolescent risk-taking behavior. Activation of the middle frontal gyrus is noted in all three tables, suggesting its key role in risk-taking and decision-making processes in adolescents. Second, the anterior cingulate cortex (ACC), found in both studies by Pei and Rodrigo, highlights its involvement in evaluating risks and making decisions. Moreover, temporal regions (TPJ and Middle Temporal Gyrus) are activated in both studies by Rodrigo et al. and Chein, indicating their role in integrating social and cognitive aspects of decision-making.
However, Pei highlights insula activation, which is crucial for processing risk and uncertainty, while Chein and Rodrigo do not mention this region prominently. The ventral striatum and orbitofrontal cortex are specifically mentioned by Chein for the interaction of age and social context, suggesting these areas are more responsive to social influences during adolescence. Finally, the precuneus, featured by Chein and Rodrigo, indicates its involvement in self-referential thinking and social cognition during risk assessment.

Data Acquisition and Analysis in Studies

Chein analyzed brain activity differences in the stoplight task between adults and adolescents, both socially and independently. Using a 3 Tesla Siemens Allegra magnet, scans included 195 acquisitions with T2*-weighted echoplanar imaging (EPI) sequence. Data analysis involved AFNI, with motion correction and normalization to MNI coordinates, smoothed with a Gaussian kernel. A single GLM equation identified fMRI signal changes during decision-making. Voxel-wise parameters outside 2.5 standard deviations were removed before group testing. Two-way repeated measures ANOVA examined age and social context effects. Statistical maps were corrected for multiple comparisons using a voxel-wise threshold ($p < .005$) and contiguity requirement, resulting in a family-wise error rate below 0.05. See Table 3.

Pei used two 3 T GE Signa MRI scanners for data acquisition with identical parameters. Functional images employed a reverse spiral sequence, and preprocessing included discarding initial volumes, slice timing correction, and spatial realignment. High-resolution structural images were normalized to the MNI template. Functional images were smoothed, and data analysis used a GLM with regressors for different task phases. Motion parameters ensured minimal head movement. Group-level analysis involved a one-sample t-test of contrast images, corrected for multiple comparisons (FDR $p < 0.05$). ROI analysis focused on stake-modulated responses and VS activation, with functional connectivity assessed using psychophysiological interactions (PPIs). Multiple OLS models examined associations between neural activation, connectivity, and behavior, corrected with the Bonferroni procedure. See Table 3.

Rodrigo conducted screening tests before inviting participants to the MRI lab. Using a 3.0 Tesla Signa Excite HD scanner, visual stimuli were presented through video-vision glasses, and choices were indicated using response controls. Data acquisition used an EPI sequence across two runs, with high-resolution T1-weighted images recorded. Processing included realignment, slice timing correction, co-registration, smoothing, and GLM analysis using SPM8. Event-related design modeled BOLD time series data with the hemodynamic response function. The analysis focused on decision phases, contrasting risk vs. ambiguity and dangerous vs. safe choices. Significant clusters were considered at $p < 0.001$, FWE-corrected. ROI activations were analyzed using the FIR algorithm, with second-level analyses exploring age and gender differences. Correlations between brain activations and individual risk behavior were conducted, using the MarsBaR toolbox for computations. See Table 3.

Table 5: Overview of imaging equipment, data acquisition, pre-processing, data analysis, and focus of selected studies.

Study	Imaging Equipment	Data Acquisition	Pre-processing	Data analysis	Focus
Chein et al. Study	3 Tesla Siemens Magnetom Allegra MRI scanner	High-res imaging (T1-weighted MPRAGE), whole-brain T2*-weighted echoplanar imaging (EPI)	Motion correction, normalization to MNI coordinates, smoothing	AFNI, voxel-wise GLM, two-way repeated measures ANOVA, corrected for multiple comparisons (FWE)	Brain activity differences in adolescents vs. adults, socially and independently
Pei et al. Study	Two 3 Tesla GE Signa MRI scanners	Reverse spiral sequence, T1-weighted images	Discarding initial volumes, despiking, slice timing correction, spatial realignment, skull-stripping, normalization, smoothing	GLM, nonparametric testing, psychophysiological interactions (PPIs), Bonferroni correction	Neural activation, functional connectivity, decision stake size, and driving behavior

Rodrigo et al. Study	GE Signa Excite HD 3.0 Tesla MRI scanner	Echo-planar imaging sequence, high-resolution T1-weight anatomic images	Realignment, slice acquisition correction, co-registration, smoothing	SPM8, voxelwise GLM, high-pass filter, FIR algorithm, MarsBaR toolbox	Decision-making in risk/ambiguity scenarios, whole-brain contrasts, age and gender differences, correlational analyses

Errors in Data Acquisition and Analysis in Studies

Simply looking at the techniques used in these three studies, some biases and limitations can already be pointed out. First, in the Chein study, the exclusion of data with significant motion may reduce the sample size even more, coupled with the relatively small participant number of 40, which may lead to statistical underpowering. Further, the use of a motion correction threshold may not fully eliminate motion artifacts. Due to the random movements of participants, even with highly complex algorithms, it may not be possible to accurately correct all errors. Further, this smoothing can obscure finer details in brain activity that may have been marked simply as outliers. This means that rapid and small-scale firing is weighted much less or even ignored completely compared to larger-sized firing, even when the scale of activation is not correlated with the significance of function.

Moreover, looking at the Pei study, a large issue is differences between scanners, which may introduce variability. Perhaps the calibration between both devices is offset, or just errors with individual machines, this is undoubtedly a source of error that shouldn't be overlooked. Next, smoothing with 8 mm FWHM might overly blur the data, and the use of a high-pass filter cutoff could miss low-frequency signals of interest, which could cause the loss of significant data in small-scale regions. This again means that rapid and small-scale firing is weighted much less or even ignored completely compared to larger-sized firing. Finally, Pei selected to use the Bonferroni correction, which is known to be conservative and reduces the power of the hypothesis.

Finally, the Rodrigo study also had several potential biases, technical limitations, and analytical issues. The small sample sizes and relaxed statistical thresholds may have led to false positives, while screening tests might have excluded diverse participants, limiting the representativeness of the findings. Technical limitations include potential distractions from video-vision glasses and the critical accuracy needed in realignment and slice timing correction processes. Analytically, the high-pass filter employed might miss slower BOLD signal fluctuations, and correlational analyses may be affected by unmeasured individual differences, potentially skewing the results.

DISCUSSION AND CONCLUSION

The meta-analysis reveals commonalities among brain regions in adolescent decision-making, mainly the middle frontal gyrus, ACC, and temporal regions. These findings underline the importance of frontal and temporal regions in integrating cognitive, emotional, and social information during risky decision-making. Future research should include more diverse samples to explore the influence of different demographic variables – such as socioeconomic status – on adolescents' decision-making processes. This will enhance the generalizability of the findings. Moreover, conducting longitudinal studies to observe neural changes over time as adolescents transition into adulthood is crucial, as this could provide insights into the development of brain regions involved in decision-making processes and the impact of environmental factors. Lastly, future studies should examine the roles of hormonal changes during adolescence in decision-making processes, as hormonal fluctuations might significantly impact risk-taking behavior and neural activation patterns. By utilizing these and other improvements, researchers stand a better chance of uncovering the mechanisms under which risky decision-making in adolescents is most active, and how to apply these insights.

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