Frontal-Subcortical Circuitry in Social Attachment and Relationships:

A Cross-Sectional fMRI ALE Meta-Analysis

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ABSTRACT

Researchers have explored the concept of attachment in multiple ways, from animal studies examining imprinting to abnormal attachment in psychopathology. However, until recently, few have considered how neural circuitry develops the effective social bonds that are subsequently replicated in relationships across the lifespan. This current cross-sectional study undertook a fMRI Activation Likelihood Estimation (ALE) meta-analyses to examine the neurocircuitry that governs emotional and behavioural functions critical for building effective social relationships in children and adults. Results suggest that dissociable dorsal cognitive ("cool") and ventral - affective ("hot") frontal-subcortical circuits (FSC) work together to govern social relationships, with repeated social consequences leading to potentially adaptive – or maladaptive – relationships that can become routinized in the cerebellum. Implications for forming stable, functional, social bonds are considered, followed by recommendations for those who struggle with cool and hot FSC functioning that can hinder the development of adaptive prosocial relationships.

Key Words: Frontal Subcortical Circuitry; Social Attachment; functional neuroimaging; Meta-analysis; Cool and Hot Executive Functions; Executive Social Control

1. Introduction

Psychological science has traditionally focused on social perception and rational choice as opposed to the more complex emotional decision-making processes critical for forming social relationships [1] . Social attachment relies on adaptive decision making that is not easily quantifiable [2-6], in part because social exchange is dynamic rather than static [7]. Social decisions can be influenced by multiple individuals that are afforded different degrees of importance to an individual, rather than one specific person in developing subsequent bonds [8]. As a result, social exchange is governed by many people and circumstances (both past and present) that lead to social action and reaction for an individual [9, 10].

Emotions also play a key role in social decision-making by attaching an affective valence to the dynamic interpersonal exchange [11-14]. Translating complex emotionally-influenced decision-making processes into concrete observations requires the examination of several interdependent variables [6, 9, 11-13, 15-17]. Emotional decision making has been informed by research on autonomic nervous system changes in response to social stimuli [18-21] and lesion studies of the ventral-medial prefrontal, amygdala, insula, and cerebellar regions [19, 20, 22, 23]. Although emotion-based learning is dissociable from the episodic memory system [6, 15, 24-26], clearly they are interrelated in forming a historical precedent for the adaptive or maladaptive behaviour an individual might display.

Teuber [27] first reported a clear dissociation between people "knowing" what they should do but, instead, "doing" something different. Thus, two systems seem to govern relationship dynamics, with quick, emotionally-driven actions seen in direct contrast to those governed by logical, reasoned, deliberate thought [28-30]. This dissociation between emotional and reasoned decision-making has been documented using several paradigms and populations, such as Bechara's [31] study showing patients saying something different than the behaviour they display, or Barkley's [32] argument that the lack of internal (self-regulating) language does not allow individuals with ADHD to inhibit prepotent responses to external stimuli. Although the impact of social exchange on personal attachment is clear, empirical efforts are needed to determine how dissociable rational-deliberate and emotional-intuitive neurocircuits influence this process.

Frontal-subcortical Circuitry in Executive Social Control

Social behavior is regulated by the frontal-subcortical and cerebral-cerebellar circuitry that is responsible for executive functions (EF) [33] governing attention to self and others [34]. EF often refers to a complex array of intentional, regulatory, self-governing processes that allow us to plan, organize, implement, monitor, evaluate, and change behavior to ensure adaptive outcomes [35-37]. Critical in managing thoughts, emotions, and actions [38, 39], EF allows an individual to keep social dynamics in working memory, sustain attention to consider social nuances, and inhibit maladaptive behaviors to flexibly consider a variety of prosocial responses during social exchange. However, simply considering EF as a single supervisory system that exerts control over emotions and behaviour limits our understanding of brain-based social development and attachment. For instance, medial frontal circuitry appears to govern motivation for action, left lateral functions provide for goal setting, and right lateral systems help monitor results [40], all of which would be crucial for effective social exchange.

Emerging evidence in EF research suggests that this construct can be divided into two interrelated but dissociable components, often referred to as “cool” (external) and “hot” (internal) EF [39, 41]. Cool EFs are defined as a set of cognitive skills involved in developing, implementing, monitoring, updating, evaluating, and modifying goal-directed behaviors for the purpose of responding to external task demands and solving problem-situations. As a result, cool EF’s require attention to external stimuli and self-directed observable behaviours to complete a task or achieve a goal. In contrast, hot EF’s add an emotional or motivational component to executive control, providing the affective valence to drive both social and cognitive behaviour [34].

Clearly, there is not one EF, but many of them, with at least five frontal-subcortical circuits (FSC) identified that govern psychosocial functioning [42], as depicted in Figure 1 [43]. In addition, the cerebral-cerebellar circuitry plays a crucial role, working to implement social, emotional, and behavioural repertoires in response to social demands [33]. Physiologically, the cool cognitive EFs are usually associated with the dorsolateral prefrontal and dorsal anterior cingulate circuitry, while hot affective EFs are usually associated with the orbitofrontal cortex and ventral anterior cingulate circuitry [34, 44, 45]. While consistent with our earlier discussion, this distinction between the thinking dorsal system and emotional ventral system is complicated by their associated structures, including the thalamic pulvinar, amygdala, hippocampus, basal ganglia, nucleus accumbens, insula, cerebellar vermis, and other cortical regions, particularly the right temporal-parietal association cortex [37, 42, 46-49]. The basis of these dissociable EF circuits lies in their differential interactions with other cortical and subcortical structures [42], with cool dorsolateral-dorsal cingulate circuitry largely linked with other cortical areas (e.g., tertiary parietal lobe), while the hot orbital-ventral cingulate circuitry is associated with paralimbic social (e.g., amygdala), reward (e.g., nucleus accumbens), and integration (e.g., insula) structures, and white matter pathways (uncinate fasciculus), all of which have been known to influence psychosocial functioning and psychopathology [50].

(Insert Figure 1 about here)

Although it is alluring to be reductionistic in considering the cool dorsal system regulating external (task-focused) EF and the hot orbital-ventral medial systems that govern internal (self-regulation) EF, acknowledging how these systems reciprocally govern adaptive social behavior is of paramount importance [34]. In addition, considerable transformation of these circuits occurs throughout neurodevelopment, before a child enters school, during adolescence, and even into early adulthood [51, 52]. In fact, the late-developing uncinate fasciculus – a critical tract important for hot ventral system functioning – is not fully developed until early adulthood [34]. However, throughout neurodevelopment there is a gradual shift from more emotional to more rational responding in social contexts [51, 53], suggesting perhaps the cool dorsal circuitry begins to supercede and perhaps even dominate the hot ventral circuitry in governing attachment in relationships, with aberrations leading to psychopathology [54]. Previous studies suggest a link between hot affective EF and social functions using ToM and reward decision making tasks (see [34]), but these functions are also physiologically and psychologically related to cool cognitive EF functions [42]. Children's EF ability to plan, inhibit, and modify responses, and to control attention allocation, may directly influence their ability to regulate their emotions and behaviors in response to social demands [55]. This suggests these two circuits are dissociable, but not orthogonal, in their influence on social behavior.

Exploring how cool dorsal and hot ventral circuits influence social dynamics across the lifespan will enhance our understanding of healthy, adaptive, social bonds, and when aberrant, how this circuitry can lead to maladaptive attachment and potentially psychopathology. In this study, Activation Likelihood Estimation (ALE) meta-analysis was used to explore FSC and CCC involvement in inhibition, reward, and empathy constructs. For cool EF (study 1), studies of inhibition were included. For hot EF, studies of decision-making tasks with incentive and risk (reward: study 2), and mentalizing and empathy tasks (theory of mind; ToM: study 3) were included. It was predicted that cross-sectional (child, adult) results would reveal a neurodevelopmental progression, with rational dorsal cool systems becoming more relevant for social functioning in adults relative to the emotive ventral hot systems thought to be dominant in children.

2. Method

Study Selection

PubMed/Medline and ScienceDirect databases were searched for relevant fMRI and PET studies through September 2016. Keywords were chosen for the Study 1: Cool Executive Functioning (“cognitive control”, “executive functioning”), Study 2: Hot Executive Functioning Reward Decision Making (“reward”, “decision”); and Study 3: Hot Executive Functioning Theory of Mind (“theory of mind”, “mindreading”, “ToM”, “mentalizing”) analyses. The inclusion/exclusion criteria were as follows:

1. Only empirical English-language studies that used fMRI or PET as the neuroimaging technique;
2. Studies with pharmacological manipulations (including placebo controlled) were excluded due to possible anticipation effects that might influence behavior/brain activation [56];

3. Only studies with whole-brain analysis were included because region of interest (ROI) studies violate the ALE meta-analysis null hypothesis that activation is equal across the brain [57];
4. Studies were included if they reported standardized MNI or Talairach coordinates and aimed at exploring cool or hot executive functioning;
5. For patient studies, only healthy control participant group data were included to avoid possible brain activation differences that may be related to neurological or mental illness;
6. For developmental studies, only studies that included within group results for healthy children or healthy adults were included; and
7. For cool EF tasks, we searched for paradigms that mainly tap on inhibition (stop vs. go; nogo vs. go) and conflict resolution (incongruent vs congruent). Frequently used paradigms include Stroop, flanker, Simon, Stimulus-Response Compatibility (SRC), antisaccade, stop-signal and go nogo tasks. Studies with working memory functions (i.e. N-Back, Sternberg) were not included in this search.
8. Due to the fact that few studies have reported such deactivations, only contrasts of increased activation were included [56, 58].

Based on the abovementioned criteria, we conducted 6 meta-analyses for the 3 studies presented here:

1. Study 1 Cool Executive Functioning
    (a) Adults: 2604 foci from 140 experiments with 2901 participants
    (b) Children: 169 foci from 16 experiments with 327 participants;
2. Study 2 Hot Executive Functioning Reward Decision Making
    (a) Adults: 5080 foci from 189 experiments with 3813 participants
    (b) Children: 807 foci from 33 experiments with 942 participants; and
3. Study 3 Hot Executive Functioning Theory of Mind
    (a) Adults: 2333 foci from 169 experiments with 4147 participants
    (b) Children: 111 foci from 12 experiments with 185 participants.

Figure 2 shows the Prisma flowchart of the process of article selection for final inclusion in the study. The studies included for all meta-analyses conducted are listed in the supplementary materials.

(Insert Figure 2 about here)

Meta-analytic Methods: Activation Likelihood Estimation (ALE)

To identify consistent cool and hot executive network activation in healthy children and young adults, the GingerALE, v 2.3.5 algorithm was used to conduct coordinate-based meta-analysis [57, 59]. This algorithm identifies brain regions showing a convergence of reported coordinates across experiments that are higher than expected under the assumption of random spatial associations. ALE considers the reported foci not as single points but rather as the centers for 3-D Gaussian probability distributions capturing the spatial uncertainty associated with each focus. The width (i.e. the full-width at half-maximum, FWHM) of these spatial uncertainty distributions was determined by between-subjects and between-template variances. The probabilities of reported foci in a given experiment were then combined into a modeled activation (MA) maps for each experiment, then combined to form a probability distribution of voxel-wise ALE scores to describe results convergence. To identify the ‘true’ convergence across experiments from random convergence, a permutation procedure was used to compare ALE scores with an ALE null distribution map.

In the current study, all Talairach space foci were transformed into a MNI brain template using GingerALE transformation algorithms. To control for multiple comparisons, the ALE map was thresholded at a false discovery rate (FDR) of $p < 0.05$, corrected. Compared to other meta-analyses using a minimum threshold of 100 mm^3 [60, 61], a slightly more conservative threshold of 200 mm^3 [58, 62] was used. ALE maps were overlaid onto the colin27_T1_seg_MNI.nii brain template in the software MRIcron (available at www.mccauslandcenter.sc.edu/mricro/mricron) for display. For comparisons that were underpowered, a more lenient uncorrected threshold of $p < 0.001$, 200mm^3 was used.

Subtraction Analysis

GingerALE contrasts of preferential brain areas activated by cool EF versus hot reward decision-making, cool EF versus hot ToM, and by hot reward decision making versus hot ToM were conducted. A 10,000 simulations permutation test of randomly distributed foci was run to determine ALE map significance. To perform subtraction analyses, individual ALE analyses were first conducted separately in each category. Then all experiments selected for the two categories were pooled and another ALE analysis was conducted on this pooled dataset. The resulting ALE maps from both individual categories and the pooled dataset were thresholded at $p < 0.05$ (FDR) and then computed through the GingerALE for subtraction analyses. To correct for multiple comparisons, the resulting ALE maps were FDR thresholded with $p < 0.05$ and a minimum cluster size of 50 voxels [63, 64].

3. Results

Results of all meta-analyses are presented in Tables 1 and 2. The FDR corrected threshold applied for significant clusters was $p < .05$. However, as studies with children were relatively underpowered, the analyses yielded no clusters at $p < .05$, FDR corrected. Thus, a less stringent threshold (uncorrected, $p < .001$, 200 mm^3) was applied to minimize false negative findings. Given this less stringent threshold for children, the subtraction analyses were only conducted for the adults.

Study 1: Cool Executive Functioning

For adults, the main ALE analysis of cool executive functioning revealed 16 significant clusters (Table 1a; Figure 3a), with the largest cluster (volume = 24,720 mm^3) located in the right insula, right inferior and middle frontal gyrus. Other clusters included the left insula, right supplementary motor area, right median cingulate, bilateral inferior and superior parietal lobule, left inferior and middle frontal gyrus, right fusiform gyrus, bilateral superior, middle and inferior occipital gyrus and right thalamus. For children, the main ALE analysis of cool executive functioning revealed nine clusters (Table 1b; Figure 3b), with the largest cluster (volume = 1,384 mm^3) located in the right inferior frontal gyrus. Other clusters included left inferior frontal gyrus, left supplementary motor area, right inferior temporal gyrus, right precentral and postcentral gyrus, left middle occipital gyrus, and right paracingulate.

(Insert Table 1 and Figure 3 about here)

Study 2: Hot Executive Functioning Reward Decision Making

For adults, the main ALE analysis of reward-decision making revealed 16 significant clusters (Table 1c; Figure 3c), with the largest cluster (volume = 59,400 mm^3) located in subcortical regions including bilateral putamen, right caudate, right amygdala, right hippocampus, bilateral thalamus and bilateral insulae. Other clusters included the bilateral ventral orbitofrontal gyrus, left superior frontal gyrus, right inferior frontal gyrus, bilateral middle frontal gyrus, right supplementary motor area, bilateral anterior cingulate, left posterior cingulate, left precentral gyrus, right middle occipital gyrus, and parietal regions including bilateral inferior parietal lobule, and left superior parietal lobule.

For children, the main ALE analysis of reward decision making revealed 15 significant clusters (Table 1d; Figure 3d), with the largest cluster (volume = 8,224 mm^3) located in the left pallidum and left insula. Other clusters included the right insula, right ventral orbitofrontal gyrus, left superior frontal gyrus, bilateral supplementary motor area, left postcentral gyrus, left anterior cingulate, right paracingulate, right caudate, right inferior parietal lobule, right cuneus, right inferior occipital gyrus and left middle occipital gyrus..

Study 3: Hot Executive Functioning- Theory of Mind (ToM)

For adults, the main ALE analysis of ToM revealed 12 significant clusters (Table 1e; Figure 3e), with the largest cluster (volume = 19,784 mm^3) located in the left angular gyrus and left middle temporal gyrus. Other clusters included the right superior and middle temporal gyrus, right ventral orbitofrontal gyrus, bilateral superior, middle and inferior frontal gyrus, bilateral insulae, bilateral supplementary motor area, , bilateral precentral gyrus, right precuneus, and left cerebellum (crus II).

For children, the main ALE analysis of ToM revealed 10 significant clusters (Table 1f; Figure 3f), with the largest cluster (volume = 888 mm^3) located in the right temporal pole. Other clusters included the right superior frontal gyrus, bilateral inferior frontal gyrus, right paracingulate, right superior, middle and inferior temporal gyrus, left angular gyrus, and left cerebellum (crus I).

Comparison 1: Cool Executive Functioning versus Reward Decision Making for Adults

The comparison of cool executive functioning versus reward processing revealed eight clusters (Table 2a; Figure 4a), with the largest cluster (volume = 608 mm^3) located in the right inferior parietal lobule. Other clusters included left inferior parietal lobule, right Supramarginal gyrus, right precentral gyrus right paracingulate, and bilateral inferior frontal gyrus, In contrast, the comparison of reward processing versus cool executive functioning revealed 6 clusters (Table 2b; Figure 4b), with the largest cluster (volume = 25,136 mm^3) located in the right olfactory cortex, extending to right amygdala, right caudate, and right putamen. Other clusters included left ventral orbitofrontal gyrus, bilateral anterior cingulate, left superior frontal gyrus, and left precuneus.

(Insert Table 3 and Figure 4 about here)

Comparison 2: Cool Executive Functioning Versus Theory of Mind for Adults

The comparison of cool executive functioning versus ToM revealed 17 clusters (Table 2c; Figure 4c), with the largest cluster (volume = 8,800 mm^3) located in the right inferior frontal gyrus. Other clusters included the left superior frontal gyrus, bilateral middle frontal gyrus, left insula, left paracingulate, left precentral gyrus, right supplementary motor area, left fusiform gyrus, right superior and inferior occipital gyrus and parietal regions including bilateral superior parietal lobule, left inferior parietal lobule, and right supramarginal gyrus. In contrast, the comparison of ToM versus cool executive functioning revealed 10 clusters (Table 2d; Figure 4d), with the largest cluster (volume = 12,544 mm^3) located in the left superior frontal gyrus. Other clusters included right ventral orbitofrontal gyrus, right inferior frontal gyrus, right superior temporal gyrus, bilateral middle temporal gyrus, and parietal regions including left precuneus, left angular gyrus, and left cerebellum (crus I).

Comparison 3: Reward Decision Making Versus Theory of Mind for Adults

The reward processing versus ToM comparison revealed 14 clusters (Table 2e; Figure 4e), with the largest cluster (volume = 411,168 mm^3) in the subcortical regions including right thalamus, right amygdala, right caudate and right putamen. Other clusters included the left thalamus, left ventral orbitofrontal gyrus, right inferior frontal gyrus, bilateral middle frontal gyrus, right paracingulate, left precentral gyrus, right middle occipital gyrus, and parietal regions including bilateral inferior parietal lobule and right anglar gyrus..In contrast, the comparison of ToM versus reward processing revealed 9 clusters (Table 2f; Figure 4f), with the largest cluster (volume = 8,032 mm^3) located in the left middle temporal gyrus. Other clusters included right superior and middle temporal gyrus, left superior, middle and inferior frontal gyrus, and left precuneus.

4. Discussion

Despite its relevance for understanding and serving the psychosocial needs of children and adults, the study of the neurobiological determinants of social attachment and bonding remains in its infancy. Empirical attention has primarily focused on *cognitive* EF, with less attention paid to *affective and social-emotional* EF [34]. Our current meta-analysis findings suggest a disassociation between the dorsal cool EF and ventral hot EF networks in both children and adults, which advances our understanding of how this circuitry might impact social relationships, and more importantly how this potentially influences social attachment throughout the lifespan. Examining how this neurocircuitry develops and interacts with other brain systems can form the foundation of healthy socio-emotional development, and potentially lead to interventions for those with impaired frontal-subcortical and cerebral-cerebellar circuity, common to many forms of psychopathology [33, 54].

In our adult meta-analyses study, the network activated for cool EF clearly emphasized the DLPFC and IFG, and the hot EF showed more ventromedial frontal activity, as was predicted. The well-studied dorsal EF functions include constructs such as planning, organizing, strategizing, monitoring, evaluating, and shifting/modifying behavior [36, 37, 65]. In social relationships and attachment, this externally focused circuitry is necessary to allow for a person to selectively attend to social cues, inhibit responses that are inconsistent with a relationship dynamic, and update social information during interpersonal exchange to ensure coherence is maintained between individuals. Also important to DLPFC function is establishing mutually beneficial, socially adaptive, goal-directed behavior, guiding individuals to focus on the relevant cues over irrelevant or distracting stimuli, which is in part based on prior experience and anticipated outcomes. This cool dorsal system allows an individual to attend to, and repair, verbal or behavioral deviations that could interfere with social goals. The dorsal system thus allows for real-time engagement between individuals for developing a sense of connection, continuity, and comradery.

Although it is plausible that dorsal network mediation of social discourse and action fulfills goal-directed behavior in some interpersonal relationships, it may be impossible to have meaningful social attachment and bonding without hot ventral circuitry. In most cases, the cool dorsal network must interact with internally guided hot ventral-medial system functions that regulate motivational states to maintain goal-directed behavior over time [40, 66]. Without affective motivation and valence, sustaining attention toward goal-directed behaviour during interpersonal exchange becomes unlikely – if not impossible. Lateral frontopolar regions likely intersect with ventral-medial affective functions to provide both emotional tone and facilitate memory encoding and retrieval [67, 68], which would be critical for updating and maintaining the goal-directed social behaviour critical for attachment over time. In children, previous EF meta-analysis [69] showed bilateral prefrontal areas (DLPFC and inferior prefrontal to insular cortex) to be activated, increasing in adolescence, similar to our findings. This suggests cool FSC becomes ever more omnipresent in the maintenance of social information during interpersonal exchange, consistent with our findings in adults of strong bilateral insular, DLPFC, mid-cingulate and inferior parietal lobule activity.

As for hot EF, our meta-analysis of reward-decision making for adults revealed both amygdala and insula activation with strong inferior frontal gyrus involvement. Hot EF is thought to be a function of the orbitofrontal and ventral-medial (including amygdala, nucleus accumbens, and ventral cingulate) circuitry [34] necessary for evaluation of a stimuli’s affective or motivational significance [39]. Evidence suggests that the development of hot EF lags behind cool EF [70, 71], yet children and adolescents seem to be governed by emotionality more than rational problem solving during social discourse relative to adults

[52]. Interestingly, the research that has been done on impairments in the hot EF, as measured by gambling [11], risky decision making (e.g., [13]), and delay discounting [72], supports the idea that impairments in hot EF can occur in the absence of cool EF, and vice versa [39]. To further this understanding, the present meta-analysis used gambling-reward incentive-type tasks [6, 73] and ToM tasks [74-76] to examine hot ventral-medial circuit functions.

Results showed the expected cool-hot circuit dissociation, with the absence of DLPFC activation in the hot EF tasks (Figures 3). This is further emphasized in our adult contrasts where DLPFC showed greater activity in cool EF compared to Reward or ToM tasks (Figures 4a and 4c) and the ventral orbital gyrus only activated in Reward or ToM tasks vs. cool inhibition EF contrasts (Figures 4b and 4d). The question remains, if the cool dorsal EF system develops more quickly than the hot ventral EF system, but children are more “emotional” in their social relationships than adults, is there a neurodevelopmental tendency to improve dorsal cognitive inhibition skills before one can eventually express ventral affective determinants of attachment in a more social appropriate manner? Explicitly stated, does this supposition suggest a neurodevelopmental trend that makes social attachments qualitatively different in childhood than in adults? Perhaps childhood attachments rely more on affective engagement and physical affection that is not necessarily tangible to children, whereas in adults this affective connection is modulated by more rational social exchanges and objective relationship criteria. However, this possibility does not suggest that affective features are absent from such “mature” bonds, since orbital-ventral medial activity in reward and ToM was actually greater in adults. Thus, these data do not resolve a critical question, namely, how does affectively dominant attachment in children evolve into a combined cool rational and hot emotive – and arguably more advanced – attachment in adulthood?

The function of the orbital-ventral medial circuits is to integrate emotional valence and motivation to influence social problem solving, modulating affect and social behavior during interpersonal exchange [34]. This modulation is done through possibly unconscious consideration of expected outcomes of action [31, 77] for adaptive [78] and potentially maladaptive response selection [79]. Cool cognitive EF is clearly influenced by hot, affective orbital-ventral medial functions based on discrepancies seen between the predicted and actual outcomes in behavior, which in turn affects motivational and affective valence. Thus, orbital-ventral medial areas do appear to work with, or complement, the dorsal system functions through subtle effects on our cognitive systems in typical populations, with more significant effects in clinical populations. For instance, the hyperactive (anxiety) or hypoactive (conduct disorder) amygdala-prefrontal responses to social situations lead to the different reactions seen in these disorders [80, 81]. Unfortunately, most of the EF measures available do not take into account hot affective EF, thus limiting our understanding of how the orbital-ventral medial circuitry impacts overt social behavior and learning [39], which in turn affects interpersonal bonds and attachment.

In the present study, adults showed activation in bilateral insulae for both cool EF tasks (e.g. inhibition and conflict resolution) and hot EF tasks (i.e. reward decision making and ToM tasks), whereas bilateral insular activity was only seen in reward decision making (hot EF) in children. The insular cortex has been reported to be involved in functional integration [50]. The insula may play a key role in associating visceral sensation and autonomic responses with cognitive appraisal of social or emotional information [82, 83]. Thus, it is thought that the lack of insular activity in children for cool EF and ToM tasks may be associated with a less well formed network for integration, suggesting more limited regulation between cool and hot EF. In terms of affective social relationships, this less developed network between the orbital-ventral frontal and insular regions may possibly lead the child to be more emotionally primed (as shown in activity in reward decision making) when reacting to a social interaction [84, 85]. In addition, a recent review paper suggested that the functional connections between ventral orbitofrontal and insular cortices may promote affective social interactions and interpersonal relationships [86]. Thus, it is important for children and adolescents to form an effective orbitofronto-insular network for social functions during these developing years.

As for reward decision making, adults had strong activity in more cool cognitive circuit areas, including the anterior and posterior cingulate, and bilateral superior parietal regions. These data could also suggests adults are more effective than children in using prior experiences during reward-based decision- making. Combined, adults would have greater cool dorsal control of hot ventral proclivities, or perhaps just better integration of the cool and hot circuity during unpredictable situations, which would be more important in adult social problem-solving. For example, adolescence is well-known for social unrest and upheaval. Not only are teens more highly influenced by peers than children or adults [84, 85, 87-89], but it is also a time when social context plays an important role in a teen's social decision-making [88, 90, 91]. Perhaps this reflects the difficult (and sometimes unpredictable) emergence of cool cognitive control over labile hot emotional valence in being the major determinant of a young adult social behaviour and relationships.

The mere presence of a peer can increase risky behavior during adolescence, possibly because the hot ventral circuitry amygdala diminishes the capacity for cool dorsal self-control and measured responsiveness, thus impairing "rational" decision making [92-94]. This hypothesis is consistent with changes in ventral striatal activity during adolescence [95], and perhaps form the basis of how frontal-striatal-thalamic circuitry begins to overtake limbic reactivity. Self-control is especially difficult for adolescents as compared to other age groups. This may be due to these neurodevelopmental changes that lead to the struggle between affective and cognitive control, especially in peer group settings. Jones et al. [96] found that positive social feedback enhanced learning among all ages, but that positive social feedback from peers led to increased premotor activity in adolescents. Thus, adolescents might be more susceptible to acting in the presence of peers, and use more immature hot affective responsiveness (either positive reward or negative punishment) instead of using cool dorsal problem solving in social situations and relationships. Perhaps this provides a biological explanation for why adolescent goal-directed behavior changes based on peer presence, and remains unstable and unpredictable. It could also explain why their stated intentions differ from behavioral outcomes.

In addition to affective valence and motivational influences for goal-directed behavior, the orbital-ventral-medial areas also appear to be critical in perspective-taking or what has been referred to as theory of mind (ToM). This system is particularly important for actually experiencing what others are feeling, as compared to social perception which is more a function of right temporal-parietal region [34]. For example, effective social engagement requires both perception of what others are saying and doing (external stimuli) and simultaneously managing one's own feelings and behavior (internal stimuli). To have true empathy, one must not only balance these internal and external stimuli, but concurrently use orbital *action* to "put yourself in the other person's shoes" and experience what another person experiences [34]. Our meta-analysis of the ToM tasks showed that adults strongly activated bilateral insulae, bilateral inferior frontal gyrus, and left cerebellum Crus II. whereas the children in the study showed more diffuse activity distributed amongst bilateral inferior frontal gyrus, temporal regions and the left cerebellum Crus I with no ventral orbital frontal involvement activity. Again, our child study may be underpowered, however, this finding is consistent with a less developed ToM in children compared to adults. The lesser extent of bilateral IFG activity seen in children also likely reflects the yet to mature system for imitation [97] and response inhibition with language internalization related to impulse control [32].

Given the reward-based study insula findings, additional speculation is warranted regarding the development of attachment in social goal-directed behavior. Results suggest children might be more self-focused during social engagement, whereas adults have the potential to balance internal (self) and external (other) focus in their more sophisticated relationships. This could account for the dramatic changes in social relationships, where immature, superficial peer bonds are eventually replaced by increasingly complex, interdependent, and mutually satisfying bonds in adulthood [98, 99]. Perhaps attachment is mostly reward-based in children, but more empathy-based in adulthood, suggesting the latter is particularly important for developing intimacy and stability in social bonds [100].

Finally, the contrasts between the two types of tasks within the hot ventral system in the more stable adult networks is worth further consideration. The reward tasks showed increased ventral orbitofrontal and bilateral basal ganglia activity spreading to the amygdala compared to the ToM tasks.

The ToM in turn showed increased activity in the dorsal orbitofrontal gyrus, left precuneus and bilateral temporo-parietal junction regions. These results are consistent with studies suggesting the posterior cingulate and precuneus regions to be more involved with introspection and internal evaluation during ToM tasks [101, 102]. However, no increase in insular activation was observed for empathy in comparison with reward. This could be in part due to task demands, where ToM tasks are perhaps more cognitive in nature (sometimes referred to as cognitive empathy), which has been found to be dissociable from emotional empathy (or empathic responding) [103]. As ToM tasks require perception rather than action, it is not surprising to observe a lack of increased insula activity, as true empathy requires action to feel what the other person is feeling [34].

5. Limitations and Future Directions

The current study is not without limitations. There were too few hot EF child studies for a typical ALE meta-analysis, thus results were under-powered. Another limitation is the cross-sectional design. In particular, due to a lack of research, the child sample included those aged 8-18 years, collapsing across children and adolescents. An examination of children, adolescents, young adults, and the elderly would be much more powerful in drawing conclusions about the neurodevelopment of these circuits and how this influences qualitative and quantitative differences in attachment. The neurodevelopment of both cool and hot EF continues through early adulthood, with major milestones achieved in early childhood and then again in adolescence/early adulthood (Giedd & Rapoport, 2010). As a result, an examination of children, adolescents, young adults, and the elderly would be much more powerful in drawing conclusions about the neurodevelopment of these circuits and how this influences qualitative and quantitative differences in attachment. In addition, hot EF may follow a prolonged trajectory of development as compared to that of cool EF, given the uncinate fasciculus is the last white matter pathway to fully develop (in the late twenties; [34]). Thus, future studies may consider a longitudinal design to understand how changes in the cool and hot circuits, and their interaction over time, influence the nature of social bonds and attachments in different stages of life.

Despite these limitations, the dorsal cool and ventral hot EF circuitries in children and adults were delineated, and found to be dissociable as would be expected given the neurodevelopment of social relationships critical for attachment. Results suggest adults recruit more cognitive control networks (e.g., dorsolateral, dorsal anterior cingulate, insula, and posterior cortical regions) during affective EF tasks compared to children. There is also a subtle shift from right to bilateral insular activity from children to adults in reward-decision making, while insular activation was observed in adults for empathy, consistent with the assumption these cool dorsal and hot ventral circuits are integrated more in adults during social exchange, allowing for more complex forms interpersonal relationships and stable attachment with significant others. The interaction of the cool dorsal and hot ventral EF networks provide a basis to help the individual learn to adapt to the external environment while maintaining awareness of his or her internal state. Early social bonds, such as those with caregivers, may provide an emotional anchor or scaffold necessary for a child to learn to balance personal reward and altruistic empathy during the growing years, allowing for more the more sophisticated and potentially life-long bonds necessary for secure, stable, attachments in adulthood.

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