Treasuring teen friendships: behavioral and neural mechanisms underlying adolescent learning and mental health in the peer context

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Chapter 6

General Discussion

THIS DISSERTATION

In this dissertation, I aimed to unravel the neural and behavioral mechanisms underlying adolescent learning and mental health in the peer context. To this end, I examined the neural processing of rewards and errors, which can be used to adapt and improve one's behavior and is thus an essential aspect of efficient learning (Ullsperger et al., 2014). The first aim of this dissertation was to investigate the neural processing of rewards and losses for peers (and self) in typically developing adolescents (**chapter 2**) and adolescents with an attention-deficit/hyperactivity disorder (ADHD) (**chapter 3**). I applied two experimental paradigms in combination with functional neuroimaging to examine the neural processing of rewards and (error-based) losses for oneself, friends, and unfamiliar peers. The second aim was to investigate the effect of different peer features (peer relationship type, friendship quality, and social status) on (observational) learning and internalizing problems in adolescence. To this end, I combined a reinforcement learning paradigm with social network metrics (**chapter 4**), and a prospective longitudinal design with self-report questionnaires and school records of grades (**chapter 5**). In this final chapter, I first present an overview of the study designs of the four empirical chapters. Subsequently, I provide a general discussion of the main findings, which is followed by future directions, practical implications, and conclusions.

OVERVIEW OF STUDIES

In **chapter 2**, I examined the neural activation underlying observing performance-based rewards and losses for friends and unfamiliar peers across adolescence. To this end, a sample of adolescents ($N = 80$; 9-16 years) observed their best friend and an unfamiliar peer perform the Cannonball task (de Bruijn et al., 2009) during an MRI session. In this task, the aim was to shoot and hit a target by stopping a moving cannon with a button press when this cannon was precisely lined up with the target. Performance-based errors (i.e., missing the target) resulted in monetary loss and performance-based hits (i.e., hitting the target) in monetary reward, where outcomes affected the player (i.e., peer) and observing participant equally. The design of this study included a realistic social context where the best friends and unfamiliar peers (i.e., youth actor confederates) were present during data collection.

In **chapter 3**, I build upon the study design in chapter 2 in typically developing adolescents by examining the neural processing of rewards and losses in atypically developing adolescents with the common mental health condition ADHD. Specifically, I investigated the neural activation underlying the anticipation and receipt of rewards and losses for the self and the best friend in adolescents with and without ADHD. To this end, a sample of male adolescents with ADHD ($N = 42$; 14-22 years) and typically developing male adolescents ($N = 56$; 13-23 years) performed a reward gambling task in the MRI scanner. In this task, they could win or lose money for themselves and their best friend by

guessing whether a coin toss would result in heads or tails. A reward cue or loss cue was first presented in the task to signal anticipation. The reward cue indicated the participants would receive a monetary reward outcome after a correct guess and no-reward outcome after an incorrect guess. The loss cue indicated that the participants would receive a monetary loss outcome after an incorrect guess and no-loss outcome after a correct guess. The design of this experimental task thus allowed for the comparison of the neural processing of rewards and losses against a neutral reference category (no-reward, no-loss). This task included a realistic social context where the participants could gain or lose monetary outcomes for their best friends (i.e., vicarious outcome processing).

In **chapter 4**, I investigated the influence of various peer features on observational reinforcement learning in early- to mid-adolescence. The peer features included in this cross-sectional behavioral study are peer relationship type (friends, neutral classmates, unfamiliar peers), friendship quality and social status (i.e., eigenvector centrality). A sample of adolescents (N = 214; 11-15 years) performed an observational reinforcement learning task (based on Burke et al., 2010; Rodriguez Buritica et al., 2016). In this observational learning task, a choice had to be made between two abstract stimuli with different reward probabilities (.8 *vs* .2). Subsequently, the participants received a reward outcome or no-reward outcome. The aim of this task was to learn by means of trial and error which stimulus had the highest reward probability. In the individual learning condition, the participants could only learn from their own choices and outcomes. In the observational learning conditions, the participants could also learn from the choices and outcomes of a befriended classmate, neutral classmate (neither liked nor disliked) or an unfamiliar peer. These co-players were identified by means of sociometric nominations on friendship and liking. Participants' and peers' social status in the classroom (i.e., eigenvector centrality) were calculated via a social network analysis.

In **chapter 5**, I build upon the study design of chapter 4 by examining the effect of adolescents' friendship quality on possible changes in their academic achievement and internalizing problems across two academic years during the COVID-19 pandemic. In this prospective longitudinal behavioral study, a sample of Dutch adolescents (N_{T1} = 250; 11-16 years) filled out self-report questionnaires on positive friendship quality (Friendship Quality Scale; Bukowski et al., 1994), negative friendship quality (Network of Relationship Inventory - Relationship Qualities Version; Buhrmester & Furman, 2008) and internalizing problems (Strengths and Difficulties Questionnaire; Van Widenfelt et al., 2003). Additionally, school records were obtained of report grades on the subjects Dutch, English and Math across four data collection points. Timepoint 1 (T1) of the data collection was a baseline before the pandemic (November 2019), on which the results of chapter 4 are also based. The subsequent data collection points were during the COVID-19 pandemic (T2: May/June 2020, T3: November/December 2020, T4: May/June 2021).

GENERAL DISCUSSION

The findings in this dissertation have implications on neural outcome processing for peers, adolescent learning in the peer context, adolescent friendships and mental health, and situational factors influencing adolescent learning and mental health. In this section, I will discuss and interpret the results along these lines.

Neural outcome processing for peers in (a)typical development

First, the results demonstrated that both typically developing adolescents (**chapter 2**) and adolescents with ADHD (**chapter 3**) showed neural activation during monetary reward processing for oneself and in the context of best friends (and unfamiliar peers) in brain regions typically involved in processing rewards (i.e., striatum, vmPFC) and highly salient information (i.e., insula, dACC, lPFC). Specifically, I observed that these brain regions were activated both while adolescents observed peers (best friends and unfamiliar peers) receive rewards that also affected themselves (**chapter 2**), and while adolescents with and without ADHD anticipated and received monetary rewards for themselves and their best friend (i.e., vicarious rewards) (**chapter 3**). Thus, gaining for self and friends, and observing peers' rewards, recruits similar reward and salience processing brain regions in adolescents.

The current findings are in line with prior research showing activation in a reward processing brain region (striatum) while observing others receive performance-based rewards and while anticipating and receiving own rewards and rewards for peers (Braams et al., 2014a, 2014b; de Bruijn et al., 2009; Morelli et al., 2015; Overgaauw et al., 2020; Silverman et al., 2015). Taken together, the current findings connect to the common currency theory, which refers to the concept that similar brain regions process rewards in non-social and social contexts (Lockwood et al., 2020; Wake & Izuma, 2017). Another explanation could be that the overlap in recruited brain regions is mainly driven by the similarly and closeness between best friends and oneself. For instance, prior research also showed similar striatum activation patterns during reward receipt for the self and friend, but differential activation patterns for antagonists (Braams et al., 2014a, 2014b). The contrast (i.e., difference) between self and antipathies is bigger than between self and friend and would be interesting to explore in future (clinical) neuroimaging studies.

These abovementioned processes are of relevance for daily life behavior and outcomes. For instance, vicarious reward processing has been linked to prosocial behavior and forms the basis for prosocial learning (i.e., learning to gain for others) (Contreras-Huerta et al., 2023; Crone et al., 2022; Lockwood et al., 2016). Prosocial behavior has been related to building positive friendships, social support, better academic achievement, and wellbeing (Carlo & Padilla-Walker, 2020; Gerbino et al., 2018; Layous et al., 2012; Wentzel, 2014). In addition, observed reward and loss processing forms the basis of observational learning. Being able to learn from observing others' outcomes is important to navigate our social worlds and adjust our behavior accordingly without having to experience everything

ourselves. To further understand how we represent outcomes and learning signals from peers it will be important for future (clinical) neuroimaging studies to include both positive and negative peer relationships (friends and antipathies) and include observational and prosocial learning paradigms in addition to vicarious outcome processing paradigms (see for paradigms Rodriguez Buritica et al., 2016, 2018; Westhoff et al., 2021).

Although I observed activation in reward-related brain regions during reward processing, I found no activation in brain regions typically involved in loss processing (e.g., pMFC, insula, dACC, lPFC) while adolescents observed their peers receive error-based losses and while they anticipated and received losses for themselves and for their best friend. This is not in line with prior research revealing pMFC and insula activation for observed errors in adults (de Bruijn et al., 2009), and research showing insula, lPFC, and dACC activation during (error-based) loss processing (for others) in adolescents and adults (Dugré et al., 2018; Monfardini et al., 2013; Peters et al., 2014). The current results showed that some of these regions (insula, dACC, lPFC) were activated during reward processing (**chapter 2 and 3**). This indicates that these brain regions may not necessarily code rewarding outcomes but are implicated in the salience network representing salient outcomes and highly relevant information (Seeley, 2019; Seeley et al., 2007; Ullsperger et al., 2010). Taken together, the current findings suggest that adolescents with and without ADHD may regard receiving and observing rewards for themselves, friends, and peers as more salient than losses.

Although I observed overlapping activation in reward-related regions for reward processing in non-social and social contexts, I found a social context effect in the social brain during observed outcome processing. That is, there was higher activation in the left TPJ while typically developing adolescents observed outcomes for an unfamiliar peer compared to for their best friend (**chapter 2**). The direction of this social context effect is not in line with my hypothesis and some prior studies showing higher TPJ activation during social decision making and interactions with friends and familiar peers compared to unfamiliar and disliked peers (Güroğlu et al., 2008; Schreuders et al., 2018b). However, other studies showed lower TPJ activation in (young) adults during social interactions with people they cared about more and while viewing pictures of loved ones compared to familiar others (Bartels & Zeki, 2000; Bartels & Zeki, 2004; Bault et al., 2015). As stated by Bault and colleagues (2015), efforts to infer intentions of others (i.e., mentalizing) decrease with closeness, which could explain the lower TPJ activation in the context of close others, such as friends. This explanation is in line with other studies showing higher TPJ activation when mentalizing and considering others' intentionality requires more effort compared to less effortful conditions (Güroğlu et al., 2011; Lemmers-Jansen et al., 2019; Schenk & Colloca, 2020). Taken together, a social brain region (TPJ) shows heightened neural sensitivity to outcomes for unfamiliar peers compared to friends, which could be related to increased effortfulness of mentalizing processes while observing outcomes for unfamiliar peers compared to friends. Future studies are needed to further examine

the directionally of activation in the social brain during observed outcome processing by including relationships with close and more distant peers (e.g., friends, neutral, unfamiliar peers, and antipathies) and a behavioral measure of related effortful mentalizing processes (see e.g., Majdandžić et al., 2016).

Next, I found that there were no age-effects in striatum activation during observation of rewards for peers (friends and unfamiliar peers), nor were there age-effects in TPJ activation during observed outcomes for peers in typically developing adolescents. Prior research showed that striatum activation increases with age and peaks around mid-adolescence for own rewards (Braams et al., 2014b; Peters & Crone, 2017; Schreuders et al., 2018a; van Leijenhorst et al., 2010). The lack of age-related changes in striatum activation in the current study could be explained by the focus on observing rewards for others, which might be less sensitive for developmental changes than own reward processing. Also, a prior longitudinal study showed a quadratic pattern with a mid-adolescent peak in striatum activation during gaining for best friends, but only for individuals with stable best friendships (Schreuders et al., 2021). Thus, specific friendship characteristics might be related to developmental changes in striatum responsiveness to rewards for peers. Although prior studies showed an age-related increase in TPJ activation (Crone & Dahl, 2012), this age-related increase wat only found for own outcome processing and not for outcome processing for friends (Braams & Crone, 2016). Possibly, outcome processing for friends and peers engages the TPJ for underlying mentalizing processing across all adolescents irrespective of their age (Güroğlu et al., 2011; Lemmers-Jansen et al., 2019; Schenk & Colloca, 2020). Future longitudinal neuroimaging studies are needed to further unravel developmental changes in reward-related and social brain regions for own outcome processing versus outcome processing for peers, also accounting for relationship features, such as stability.

Finally, the results demonstrated that there were no group differences in neural activation during the anticipation and receipt of outcomes between adolescents with ADHD and typically developing adolescents (**chapter 3**). However, prior research revealed group differences in neural activation with individuals with ADHD showing reduced VS activation during reward anticipation (Hoogman et al., 2011; Plichta & Scheres, 2014; Scheres et al., 2007; Ströhle et al., 2008). These different results could be explained by developmental differences, as the prior research revealing group differences was mostly performed in adults, whereas prior studies in adolescents on reward anticipation also showed no group differences in neural activation (Paloyelis et al., 2012; Von Rhein et al., 2015). An alternative explanation for the absence of group differences is that ADHD is a heterogeneous disorder consisting of multiple subgroups based on differential clinical behavioral profiles (e.g., inattentive, hyperactive, or combined subtype) and neurobiological profiles. Prior fMRI research has indeed identified subgroups of children with ADHD based on attenuated reward-related brain activation (Lecei et al., 2019). The predominantly inattentive subtype

is overrepresented in more than half of the current sample of adolescents with ADHD compared to the average prevalence of the predominantly inattentive subtype in about a third of all adolescents with an ADHD diagnosis (see meta-analysis Salari et al., 2023). A recent systematic review demonstrated neurobiological differences between ADHD subtypes showing altered connectivity in the frontal striatal thalamic network in the combined ADHD subtype and altered connectivity in the frontoparietal network in the predominantly inattentive subtype (Saad et al., 2020). Future longitudinal neuroimaging studies are needed that account for developmental differences and the heterogeneity in the ADHD diagnosis, as well as examine functional connectivity in various brain networks.

In addition, I observed that a symptom-level approach showed that more inattention symptoms related to higher vmPFC activity while adolescents received losses for themselves compared to for their best friend (**chapter 3**). The vmPFC has been implicated by prior research in personal and vicarious outcome processing (Brandner et al., 2021; Morelli et al., 2015), and learning to gain rewards for others (i.e., prosocial learning; Lockwood et al., 2016; Westhoff et al., 2021).The current results might indicate that adolescents with more inattention symptoms focus more on losses for themselves compared to for others. This focus of attention on self versus others with increasing inattention symptoms is in line with prior literature showing attentional impairment in individuals with ADHD to social cues (Marotta et al., 2014). Further research is needed to examine the effect of ADHD symptoms on the (neural) sensitivity for own versus other's outcomes and the benefits of social learning and building social relations in this population. This could ultimately give insights for clinical practice and social interventions as it might be advantageous to encourage attention for others and social learning in individuals with inattention symptoms.

Adolescent observational and academic learning in the peer context: friendship & social status

First, the findings revealed that the learning performance of adolescents benefitted from observing the choices and outcomes of peers (**chapter 4**). In line with prior research in children and adults, the current results revealed more accurate performance and quicker improvement in adolescents' observational reinforcement learning compared to individual reinforcement learning (Burke et al., 2010, Rodriguez Buritica et al., 2016, 2018). Prior research on observational reinforcement learning showed that children imitated the choices of peer models more than the choices of adult models (Rodriguez Buritica et al., 2016), which suggests that observational learning from peer models is especially beneficial during development. However, the current findings showed no effect of friendship on observational reinforcement learning, nor was there a moderating effect of positive and negative friendship quality. That is, the learning performance of adolescents benefitted equally from observing befriended classmates, neutral classmates, and unfamiliar peers.

Together, the current findings highlight adolescence as a period of observational learning opportunities from different types of peers.

In contrast to the current findings, prior dynamic learning studies showed that adolescents learn better from befriended learning partners than nonfriends, and especially if the adolescents reported higher friendship quality for these learning partners (DeLay et al., 2014; Hartl et al., 2015). A possible explanation for these different findings is that friends, compared to nonfriends, could have a stronger influence on learning performance in more dynamic learning environments that facilitate direct social interactions between friends, which would be more similar to the typical school learning environment. The learning task that I used was more static, where the participants could only observe the choices of peers and not interact with them. Previous research has also demonstrated that micro-social interactions between friends, such as positive verbal reinforcement, can influence learning performance (Sebanc et al., 2016; Vitaro et al., 2009). Another explanation may be that friendship could have stronger effects on learning in at-risk youth, such as youth with a low social status or low socio-economic status. For example, prior research showed a stronger beneficial effect of friendships on school belonging in marginalized groups (Delgado et al., 2016). Another study showed that the academic achievement of high versus low social status peers influences adolescents' friendship preferences and ultimately their academic development (Laninga-Wijnen et al., 2019). Thus, it is important for future studies to include interactive social learning paradigms and examine possible moderating effects of socio-economic status and own and peers' social status (e.g., acceptance, popularity, and centrality) on the relationship between friendships and learning outcomes.

Second, the current results did not show any effects of participants' own social status (i.e., eigenvector centrality) and the social status of befriended classmates and neutral classmates on participants' observational learning performance. In line with these findings on observational learning, participants' own eigenvector centrality was also not related to their academic achievement (**chapter 4**). Another recent study illustrated that the tendency of adolescents to use social information from peers does not increase with participants' own social status (i.e., eigenvector centrality), but this tendency increases with the social status of peers (Gradassi et al., 2022). This prior study that found an effect of peers' social status examined decision-making conformity with a social information task. Conformity (social influence) may be more prominently related to social status of peers than observational learning. Future studies are needed to further disentangle the (interaction) effects of adolescents' own and peers' social status on different types of social learning (e.g., observational learning, prosocial learning, conformity learning, and learning to trust others).

Third, I examined how observational learning could benefit academic achievement. That is, being able to learn from mistakes of others in the classroom setting may give more information to students and benefit their performance on school-related outcomes. Here, I did not find a relation between adolescents' observational learning performance

in an experimental paradigm and their academic achievement (**chapter 4**). This could indicate that observational reinforcement learning does not directly benefit and transfer to adolescents' academic achievement in the classroom setting. Additionally, having positive relationships and high-quality friendship may benefit academic achievement through social support provided by these friends (Sebanc et al., 2016). However, in line with my findings on adolescents' observational learning, positive and negative friendship quality were not related to academic achievement (**chapter 4**). Building on these prior pre-pandemic findings, the longitudinal findings also showed that there was no protective effect of positive and negative friendship quality on (changes in) adolescents' academic achievement across two academic years during the COVID-19 pandemic (**chapter 5**). Taken together, I found that there is no effect of friendship quality on adolescents' observational learning and academic learning. A possible explanation for these results is that the variation (i.e., range) of positive and negative friendship quality is low in the samples. Most participants reported friendship quality for their first or top three best friend(s) and examining a larger group of ranked friends with varying levels of friendship quality might yield different results. Prior research has indeed shown an effect of ranked-friendship preference (i.e., order effects of friends) on adolescents' behavior with friends (Markievicz et al., 2001). Thus, it would be an interesting direction for future research to examine the possible moderating effect of ranked-friendship preference on the relationship between friendship quality and adolescents' learning outcomes. Alternatively, support from other social relationships than friendships, such as parents, could possibly have a stronger impact on learning. Indeed, a pre-pandemic study found that only parental involvement, but not friendship quality, was related to academic learning (Lynch et al., 2013). Parents support could have especially influenced adolescent learning during the COVID-19 pandemic due to the lack of opportunities to study with friends during lockdowns and social-contact restrictions. In line with this, a prior study in adolescents during the pandemic found that parental support, but not friend support, buffered decreases in academic motivation during online school days (Klootwijk et al., 2021). Future studies could benefit from incorporating variables examining the broader social network of adolescents in addition to the peer network, such as parent support and teacher support. This could shed a light on which support network (e.g., friends, high status classmates, parents, teachers) would be most influential for whom and which learning context and situation would yield the most optimal learning outcomes.

Adolescent friendships and mental health

The results demonstrated that adolescents with better (i.e., higher positive and lower negative) friendship quality reported fewer internalizing problems across all timepoints pre-pandemic and during the pandemic (**chapter 5**). Accordingly, two previous studies conducted in adolescents in the beginning of the pandemic in 2020 showed a relationship between higher pre-pandemic friendship quality and fewer internalizing problems during

the pandemic (Bernasco et al., 2021; Houghton et al., 2022). The results of the current dissertation extend these previous findings by illustrating that the significant relationships between friendship quality and internalizing problems holds across an extensive period of two academic years during the pandemic in 2020 and 2021. Moreover, I found that both higher positive and lower negative friendship quality were related to fewer reported internalizing problems. This suggests it is potentially important to both maintain positive friendship quality (e.g., security) and reduce negative friendship quality (e.g., conflicts) with friends to improve adolescent mental health. Thus, adolescence can serve as a window of opportunity to improve mental health by fostering high-quality friendships. However, it should be noted that our analyses are not causal, but correlational. Thus, my findings could suggest that better friendship quality protects against the development of internalizing problems, or that fewer internalizing problems facilitates the better-quality friendships. Future studies are needed to further unravel the possible causal protective effect of friendship quality on internalizing problems, for example by means of a randomized controlled design and/or a longitudinal design to investigate friendships from the starting point of formation (e.g., start of a new school after transition) (Hariton & Locascio, 2018).

Additionally, the findings showed that there were no group differences in relationship closeness with friends between adolescents with ADHD and typically developing adolescents (**chapter 3**). Specifically, I did not find group differences in positive friendship quality, negative friendship quality, and closeness with the best friend. These findings suggest that the adolescents with ADHD perceive their friendships as close and positive comparable to typically developing adolescents. Possibly, youth with ADHD mostly experience problems in the general peer group (e.g., neglect, rejection, victimization), as reported by prior studies (Gardner & Gerdes, 2015; Mikami, 2010; Mikami & Normand, 2015), but might not experience similar problems in friendship quality. In line with the current results, recent studies also showed that adolescents with ADHD can form and maintain a close friendship (Glass et al., 2012; Rokeach & Wiener, 2020, 2022). Potentially, peer group interventions focusing on social skills training in youth with ADHD (e.g., Cordier et al., 2018; Morris et al., 2021) could benefit from expanding the social skills that they already applied in their close (best) friendships to the general peer group.

Situational factors influencing adolescent learning and mental health

As expected, I found a decrease in adolescents' academic achievement over time across two academic years during the COVID-19 pandemic (**chapter 5**). Specifically, adolescents had lower academic achievement in the second academic year (2020-2021) than in the first academic year (2019-2020) of this study. The adolescents experienced the societal and social pandemic-related restrictions for a longer time during the second year of the study, which also comprised the possible negative impact of online education on academic achievement. These findings are in accordance with a systematic review that demonstrated

learning losses in children and adolescents during the COVID-19 pandemic compared to pre-pandemic years (Panagouli et al., 2021). Although the current data cannot directly demonstrate the specificity of the learning losses during the pandemic compared to pre-pandemic years, other studies have shown that the grades of Dutch high school students were found to be more stable in pre-pandemic years (2016-2017; 2018-2019) compared to the decrease in grades found during the pandemic (2020-2021; Zijlstra et al., 2021).

As expected, I found an increase in adolescents' internalizing problems over time across two academic years during the COVID-19 pandemic (**chapter 5**). Specifically, adolescents reported more internalizing problems in the second academic year (2020-2021) than in the first academic year (2019-2020) of this study. The adolescents experienced the pandemic-related restrictions for a longer time during the second year of the study, which also comprised the possible negative effect of the social isolation and social-distancing measures. The results are in line with previous studies showing that adolescents reported an increase in internalizing problems since the start of the pandemic in the first pandemic year 2020 (Ellis et al., 2020; Li et al., 2021; Weissman et al., 2021). In accordance, studies conducted later compared to earlier in the first year of the pandemic (2020) found a higher prevalence rate of children's and adolescents' anxiety and depression symptoms (see meta-analysis Racine et al., 2021). The results of the current dissertation extend these prior results by revealing that adolescents reported more internalizing problems later in the COVID-19 pandemic (November/December 2020, May/June 2021) compared to the beginning of the pandemic (May/June 2020) and before the pandemic (November 2019). Although the current data cannot directly demonstrate the specificity of increased internalizing problems during the pandemic compared to pre-pandemic years, a recent meta-analysis demonstrated that the prevalence of anxiety and depression symptoms during the first year of the pandemic have doubled compared to pre-pandemic prevalence estimates (Racine et al., 2021).

The current findings provide some implications for society and scientific practices when confronted with a similar crisis as the COVID-19 pandemic. Future governmental policies on societal and social-contact restrictions and (school) lockdowns during a similar crisis as the COVID-19 pandemic should consider the adverse effects that it can have on the cognitive and mental health outcomes of adolescents. Furthermore, situational factors such as the pandemic can have drastic impacts on study designs and plannings and highlight the importance of flexibility. Studying a developmental population and applying a longitudinal research design was especially challenging in a time where there was no access to schools to acquire data. The data for the longitudinal study in the current dissertation was mostly acquired via an online data platform (Qualtrics), and a good rapport with the coordinating teacher at the school proofed to be highly valuable for distributing the online questionnaires. It is important for future research to anticipate situational characteristics that can affect the study, for example by using flexible online platforms

for acquiring questionnaire and task data and acquiring contact information and consent from all the participants (and parents/caregivers in case of minors) to reach out to them for follow-up sessions.

FUTURE DIRECTIONS AND PRACTICAL IMPLICATIONS

In this section, I will further discuss several directions for future research based on the current findings and the implications for educational and clinical practice and scientific practices.

Social context in experimental designs

The experimental paradigms described in the current dissertation all included a realistic social context of friends (and peers) that was established either by interacting with actors, observing friends in tasks, performing tasks with consequences for friends, or including classmates in paradigms by means of sociometric methods. During most tasks the participants took turn in performing or observing the peer perform the task, which resembles real-life interactions with peers. The inclusion of these real-life defined categories of peer relationships (e.g., friends, neutral classmates, unfamiliar peers) during outcome processing and learning tasks also enhances the ecological validity of these tasks as learning in school also often takes place in the social context of peers. For future studies it would be beneficial to include direct social interactions with peers in interactive learning paradigms, which more closely resamples learning in educational practice, to further increase the credibility of the social manipulation and ecological validity of the results.

Future research could build upon my study designs by including the real-life complex social context in research designs. First, prior research has demonstrated an impact of negative peer relationships (i.e., antipathies) and parental support and involvement on academic motivation and learning (Card, 2010; Klootwijk et al., 2021; Lynch et al., 2013). Thus, future studies could benefit from including additional peer relationship types (e.g., antipathies, popular peers) and adult models (e.g., parents, teachers) to thoroughly examine the effect of the broad social context on adolescent outcome processing and learning. Second, the complex social lives of adolescents can be followed by means of a longitudinal design with sociometric methods in a closed network, such as school classes. These sociometric methods can provide information on adolescents' social status (e.g., eigenvector and closeness centrality), individual's position in the peer group (e.g., popularity, acceptance, rejection), dyadic peer relationships (e.g., friendships, antipathies) and classroom cohesion from multiple sources within this network (i.e., classmates) (see also Güroğlu & Veenstra, 2021). Changes in these peer and social network features across development could be related to (neural) changes in learning (e.g., social learning

paradigms, report grades) and mental health outcomes (e.g., psychopathology symptoms) by means of longitudinal methods.

Symptom-level and longitudinal approach in mental health research

The results in this dissertation highlight the importance of adopting a symptom-level approach, which has also been adopted in recent clinical studies and is supported by taxonomies of dimensional ADHD symptoms (Coghill & Sonuga-Barke, 2012; Van Hoorn et al., 2022). This symptoms-level approach also offers unique opportunities for future research to study relations with behavior and neurobiology from a transdiagnostic perspective. For example, a symptom-level approach can be applied to identify transdiagnostic psychopathology dimensions (e.g., inattention, social maladjustment) that can be related to specific social and learning outcomes and neural networks (Astle et al., 2022; Barch, 2017; Holmes et al., 2021). Thus, it is valuable for future studies to adopt a symptom-level approach to examine relationships between transdiagnostic mental health dimensions, peer features, learning outcomes and underlying neural networks. Moreover, a longitudinal design is valuable for clinical neuroimaging studies as this could reveal possible biomarkers for the development of psychopathological symptoms. For example, a recent longitudinal fMRI study suggested that reduced mPFC activation during reward anticipation in adolescents could be identified as a biomarker for persistent ADHD symptoms throughout adolescence (Chen et al., 2022).

Educational and clinical implications

The current findings highlight adolescence as a period of observational learning opportunities from different types of peers (friends, neutral classmates, and unfamiliar peers). This result can be implemented in educational practice by further encouraging peer learning (e.g., buddy systems, team assignments or peer tutoring) in the classroom setting to improve learning outcomes. In line with this recommendation, prior meta-analyses indeed showed a positive effect of peer tutoring in the school setting on the academic learning performance of students, especially in secondary schools (Leung, 2015, 2019). The current results showed that using information from different types of peers can benefit adolescents' learning performance, but it still needs to be examined for whom peer learning is most beneficial and in which learning contexts and situations it yields the most optimal result.

Additionally, the current results show that adolescence can serve as a window of opportunity to improve mental health by fostering high-quality friendships. Specifically, the findings highlight the potential importance for prevention and intervention programs to stimulate and foster positive friendship quality (e.g., security) and reduce negative friendship quality (e.g., conflicts with friends) to ultimately diminish internalizing symptomatology. Prior intervention programs already included social skills training to reduce internalizing

symptoms and psychopathology (e.g., Mueller & Cougle, 2023; Weiss et al., 2003), and it would be a valuable addition to stimulate friendship quality among adolescents.

Implications for scientific practices: open science and outreach

Three of the studies discussed in this dissertation are preregistered on the open science framework (OSF). I preregistered the study designs, methods, hypotheses, and analysis-plans after the data collections, but before conducting the analyses. This allowed for transparency on which hypotheses were supported by the findings or not, including reports of null findings. The null findings presented in the current dissertation provide valuable insights, such as the lack of friendship effects on adolescents' academic and observational learning and the lack of group differences (ADHD *vs* typically developing) in neural processing of (vicarious) outcomes. Preregistrations could reduce the risk against publication bias and questionable research practices, such as HARKing, cherry picking and p-hacking, whereas it increases transparency of research practices and is an important step towards open science (Hardwicke & Wagenmakers, 2023; Yamada, 2018). Additionally, I uploaded a preprint of one paper on Research Square, which allowed for exposure of these findings via a free public version of the paper to a wide audience (Hoy, 2020). I believe that it is important for researchers to transparently share hypotheses, study designs and (null) findings via preregistrations and preprints to reduce bias and move towards open science that is accessible for a large community.

Furthermore, I communicated some of the research findings to a wide audience of children, adolescents, and parents by means of outreach projects. In collaboration with other researchers and focus groups of youth, we created animation movies on brain development and learning and shared the findings with schools and a wide audience of youth and parents on a science festival for children (Expeditie Next) and via a museum website (Corpus). Additionally, in collaboration with other PhD students I wrote an article on social learning in an open access scientific journal for youth (Frontiers for Young Minds), which was also reviewed by youth. I believe that it is meaningful for scientists to share research findings with the study population (in this case youth) via outreach initiatives to make scientific findings accessible and increase awareness of these findings in the population in question.

CONCLUSIONS

In conclusion, this dissertation focused on the neural and behavioral mechanisms underlying adolescent learning and mental health in the context of peers and friends. The neuroimaging findings revealed that reward processing for self and peers rely on common reward-related brain regions, whereas a social brain region (TPJ) showed social specificity to observed outcomes for unfamiliar peers compared to friends. Moreover,

typically developing adolescents and adolescents with ADHD show neural sensitivity in reward and salience brain regions towards rewards for themselves, friends and peers compared to losses. There were no group differences in neural processing of (vicarious) outcomes between adolescents with and without ADHD, yet a symptom-level approach showed more neural sensitivity for own compared to friends' losses in individuals with more inattention symptoms. My behavioral findings indicated that adolescents' learning performance benefitted from observing the choices and outcomes of peers irrespective of the relationship with this peer. The results did not show effects of friendship (quality) and social status on observational and academic learning, but there was a protective effect of friendship quality on internalizing problems. Taken together, these findings highlight adolescence as a period of observational learning opportunities from different types of peers. Adolescence can also serve as a window of opportunity to improve mental health by fostering high-quality friendships. Future research can build upon the current findings by adopting broad social context variables in study designs and a symptom-level approach to examine the relation between social context variables and mental health. Finally, the results can ultimately contribute to peer learning interventions in educational practice and friendship interventions to improve adolescent mental health.

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