Attention-deficit/hyperactivity disorder (ADHD) is a neurodevelopmental disorder (American Psychiatric Association, 2013) with a prevalence of 5 to 7% in children (Polanczyk, Silva de Lima, Lessa Horta, Biederman, & Augusto Rohde, 2007; Thomas, Sanders, Doust, Beller, & Glasziou, 2015; Willcutt, 2012). Boys are two to three times more often diagnosed than girls (Bauermeister et al., 2007; Ramtekkar, Reiersen, Todorov, & Todd, 2010; Willcutt, 2012). The main symptoms of ADHD are inattention, hyperactivity, and impulsivity (American Psychiatric Association, 2013). Inattention expresses as daydreaming, distractibility, difficulty sustaining attention, overlooking details, difficulty following instructions, difficulty organizing, loosing things, and forgetfulness. Hyperactivity-impulsivity manifests as fidgeting, leaving seat, restlessness, talking excessively, interrupting others, and difficulty waiting turn. Based on the symptom presentation, three subtypes of ADHD are defined, i.e., the predominantly inattentive subtype, the predominantly hyperactive/impulsive subtype, and the combined subtype. Although ADHD was historically regarded as an exclusively childhood disorder, a substantial proportion (35 to 65%) of children remains suffering from ADHD into adulthood (Barkley, 2015). Generally, symptoms of hyperactivity-impulsivity decline and symptoms of inattention persist into adulthood (Davidson, 2008). To meet the diagnostic criteria for ADHD, the symptoms must negatively affect social and educational (or, in adulthood, occupational) functioning (American Psychiatric Association, 2013).

With regard to educational functioning, students with ADHD exhibit more task-irrelevant behaviors within the classroom as compared to typically developing peers (DuPaul & Stoner, 2014; Kofler, Rapport, & Matt Alderson, 2008; Platzman et al., 1992). This finding is not surprising as the core symptoms of ADHD are opposite to classroom demands. For example, whereas students are expected to focus attention on instructions or schoolwork, ADHD is characterized by daydreaming, distractibility, and difficulty sustaining attention. On top of this off-task behavior related to symptoms of inattention, students with ADHD often exhibit disruptive behavior within the classroom (e.g., leaving seat, talking excessively, and interrupting classmates), which relates to symptoms of hyperactivity-impulsivity (Daley & Birchwood, 2010). The behavioral symptoms of ADHD may lead to stress among teachers and classmates (Greene, Besztercsey, Katzenstein, Park, & Goring, 2002; Mulholland, Cumming, & Jung, 2015; Wheeler & Carlson, 1994) and also have a negative impact on the educational outcomes of students with ADHD themselves. For example, there is a negative association between inattention problems and academic achievement (Polderman, Boomsma, Bartels, Verhulst, & Huizink, 2010). Not surprisingly, individuals with ADHD are at risk for underachievement, grade retention, special educational placement, and school dropout (Barkley, 2015; Frazier, Youngstrom, Glutting, & Watkins, 2007; Loë & Feldman, 2007; Reid, Maag, Vasa, & Wright, 1994). Besides the behavioral symptoms, deficits in cognitive function are likely to contribute to the educational impairments in ADHD. Many individuals with ADHD demonstrate problems in executive functions (e.g., attention, working memory, planning, flexibility), which has been associated with a decrease in academic achievement and increased risk for grade retention (Biederman et al., 2004; M. Miller, Nevada-Montenegro, & Hinshaw, 2012; Thorell, 2007).
With regard to **social** functioning, individuals with ADHD experience several difficulties in relationships with peers. Compared to typically developing peers, children with ADHD are less socially preferred, and are more likely to be socially isolated and rejected by peers (Hinshaw, 2002; Hoza et al., 2005). Furthermore, children with ADHD have fewer reciprocal friendships, which are often less stable and of lower quality (Hoza et al., 2005; Normand et al., 2013, 2011). It is likely that the impulsive and disruptive social behavior of children with ADHD contribute to these difficulties in peer functioning (Nijmeijer et al., 2007), which in turn may induce less positive social interactions and lead to impaired development of social skills (Kok, Groen, Fuermaier, & Tucha, 2016; Mikami & Hinshaw, 2003). Impairments in social functioning in ADHD have been further associated with deficient social cognition. For example, individuals with ADHD demonstrate deficits in theory of mind and emotion recognition, particularly for anger and fear expressions (see meta-analytic review of Bora & Pantelis, 2018).

Besides difficulties in educational and social functioning, ADHD has been associated with increased **risk-taking** behaviors, which may negatively affect daily functioning and well-being. For example, individuals with ADHD experience more frequently and more severe accidental injuries (e.g., trauma, burns, and poisonings) than individuals without ADHD (Barkley, 2001; Nigg, 2013). Furthermore, youth and adults with ADHD demonstrate more dangerous driving behaviors and are more often involved in traffic accidents (Barkley, Murphy, Dupaul, & Bush, 2002; Rosenbloom & Wultz, 2011; Thompson, Molina, Pelham, & Gnagy, 2007). Increased risk-taking in individuals with ADHD is further expressed as higher rates of substance use and abuse (e.g., nicotine, alcohol, and drugs; S. S. Lee, Humphreys, Flory, Liu, & Glass, 2011; Rooney, Chronis-Tuscano, & Yoon, 2012), criminality (Mannuzza, Klein, Abikoff, & Moulton, 2004; Mannuzza, Klein, & Moulton, 2008), risky sexual behaviors (Flory, Molina, Pelham, Gnagy, & Smith, 2006), and pathological gambling (Breyer et al., 2009; Faregh & Derevensky, 2011). The severity of ADHD symptoms and deficits in executive functions seem to play a role in the risk-taking behaviors of individuals with ADHD (Barton & Schwebel, 2006; Karazsia, Guilfoyle, & Wildman, 2012; Kollins, McClenonn, & Fuemmeler, 2005; Stavrinanas et al., 2011).

**Motivation and reward sensitivity**

The exact mechanisms underlying the impairments in ADHD are not yet fully understood. Besides the behavioral and cognitive characteristics of ADHD, many theoretical models of ADHD assume that motivational deficiencies may contribute to the impairments in individuals with ADHD. Firstly, ADHD has been associated with a low level of **intrinsic motivation** (Borcherding et al., 1988; van der Meere, Shalev, Börger, & Gross-Tsur, 1995), which is the self-desire to engage in certain behavior because of interest or enjoyment. Regarding the educational setting, this lack of intrinsic motivation in ADHD expresses as a preference for easy work, less enjoyment of learning, less persistence, and a greater reliance on external than on internal standards to judge one’s own performance, relative to typically developing students (Carlson, Booth, Shin, & Canu, 2002). With regard to social functioning,
it is unclear to which extent the difficulties derive from a reduced motivation for social stimuli. However, ADHD shares many characteristics and often co-occurs with autism spectrum disorder (ASD; Leitner, 2014; Rommelse, Geurts, Franke, Buitelaar, & Hartman, 2011; Taurines et al., 2012), which is associated with a reduced social motivation (Chevallier, Kohls, Troiani, Brodkin, & Schultz, 2012). Secondly, ADHD has also been associated with altered extrinsic motivation as reflected in an aberrant sensitivity to reinforcement contingencies, such as reward and response cost (see review of Luman, Oosterlaan, & Sergeant, 2005). The current thesis focuses on reward sensitivity, which refers to the anticipation of and response to external reward.

Rewards (e.g., money, food, and social approval) play an important role in goal-directed behavior. The processing of reward consists of specific psychological components, which are mediated by different brain circuits (Berridge & Robinson, 2003; Berridge, Robinson, & Aldridge, 2009; Kohls et al., 2014). The first reward component is ‘wanting’ (or ‘incentive salience’), which refers to the motivational aspect of reward during reward anticipation. ‘Wanting’ has been predominantly associated with the dopamine system and activation of the ventral striatum. The second reward component is ‘liking’, which corresponds to the hedonic experience during reward consumption. ‘Liking’ has been primarily associated with the opioid system and activation of the ventromedial prefrontal cortex, particularly the orbitofrontal cortex. The third reward component, learning, refers to the acquisition of information about predictive relationships between stimuli and actions, and occurs throughout the reward cycle. The reward circuitry also comprises more category-specific reward brain areas (Grabenhorst & Rolls, 2011; Rademacher et al., 2009). For example, social approval has been primarily associated with activation of the amygdala, whereas monetary reward consumption has been predominantly related to activation of the thalamus (Rademacher et al., 2009). Furthermore, the neuropeptide oxytocin seems to facilitate reward processing, especially

Figure 1.1. Reward network in the brain. From Neurobiology of Attention Deficit Hyperactivity Disorder (ADHD) – A Primer. (2019, March 21). Retrieved from https://psychscenehub.com/psychinsights/neurobiology-of-adhd/
with regard to social stimuli (Rademacher, Schulte-Rüther, Hanewald, & Lammertz, 2015). Figure 1.1 shows a representation of the reward network in the brain.

Many theoretical models of ADHD provide a neurobiological explanation for altered reward sensitivity in ADHD (see review of Luman, Tripp, & Scheres, 2010). The ‘Dynamic developmental theory’ (Sagvolden, Johansen, Aase, & Russell, 2005) proposes hypofunctioning of the mesolimbic dopamine system in ADHD as expressed as lower levels of tonic dopamine. The ‘dopamine transfer deficit theory’ (Tripp & Wickens, 2008) also assumes dysfunction of the dopamine system in ADHD. However, this theory hypothesizes diminished anticipatory dopamine cell firing, i.e., altered activity of phasic dopamine (rather than lowered tonic dopamine as proposed by the dynamic developmental theory). Some other theories assume that deficits in the activation of prefrontal pathways contribute to aberrant reward sensitivity in ADHD (Nigg & Casey, 2005; Sonuga-Barke, 2002, 2003). The ‘dual pathway model’ (Sonuga-Barke, 2002, 2003) hypothesizes that reduced dopamine efficiency results in deficient activation of at least two independent neural circuitries, which subserve executive functions (fronto-dorsal striatal circuit) and reward processing (fronto-ventral striatal circuit). According to this model, altered reward processing in ADHD is associated with deficits in the fronto-ventral striatal reward pathway. The ‘integrative theory of ADHD’ (Nigg & Casey, 2005), by contrast, assumes that aberrant reward processing in ADHD is associated with inadequate initiation of top-down prefrontal structures caused by a reduced ability to predict and evaluate reinforcers (rather than a primary deficient dopamine system as proposed by the dual pathway model). The ‘Go/No-Go learning model’ (Frank, 2005; Frank, Santamaria, O’reilly, & Willcutt, 2007) is a neurocomputational model that hypothesizes that a low striatal dopamine level is responsible for deficits in reward processing in ADHD (particularly ‘go’ learning from positive reinforcement), whereas independent disturbances in noradrenaline transmission account for response variability in ADHD. Finally, the (extended) ‘temporal difference model’ (Williams & Dayan, 2005) acknowledges the role of dopamine (both hypo- and hyperfunctioning) in reward-based learning but suggests that several learning and behavioral parameters influence reward-based learning in ADHD. All these theoretical ADHD models entail several behavioral and neurobiological predictions regarding reward sensitivity in ADHD. Unfortunately, these hypotheses are not differentiating the ‘wanting’ and ‘liking’ component of reward. Some of these predictions have been experimentally tested, particularly using tangible rewards, whereas others have to be tested in future research (Luman et al., 2010).

To date, research has provided many insights in reward sensitivity in ADHD (Luman et al., 2005, 2010). A common finding is that rewards, such as money, have a positive impact on the motivation and task performance of individuals with ADHD (Luman et al., 2005). Relative to comparison individuals, individuals with ADHD often benefit to a higher extent from rewards, particularly when reward delivery is highly frequent. ADHD has been further associated with alterations in temporal discounting of rewards (see meta-analytic review of Jackson & Mackillop, 2016), which is the extent to which a person devalues a reward with increasing time delay. In comparison to
individuals without ADHD, children and adults with ADHD generally discount money at a higher rate, meaning that they are more likely to prefer a small, immediate reward over a larger, delayed reward. Furthermore, there is some evidence for deficient reward-based learning in ADHD (Frank et al., 2007; Groen et al., 2008; Luman, Van Meel, Oosterlaan, Sergeant, & Geurts, 2008; Thoma, Edel, Suchan, & Bellebaum, 2018). With regard to neurobiological responses to rewards, individuals with ADHD demonstrate decreased ventral striatum activation during reward anticipation in comparison to individuals without ADHD (see meta-analytic review of Plichta & Scheres, 2014). ADHD has been further associated with disruptions in the dopaminergic fronto-striatal circuitry, which plays an important role in reward processing (Durston & Konrad, 2007; Rommelse et al., 2011; Taurines et al., 2012).

**Thesis outline**

The aim of the current thesis is to provide a comprehensive overview of neuropsychological and educational aspects of reward sensitivity in ADHD. The first part on neuropsychology examines the sensitivity to probabilistic rewards in gambling tasks (Chapter 2) and to social rewards (Chapter 3) in individuals with ADHD. ADHD is associated with increased risk-taking in daily life. Gambling tasks that make use of probabilistic rewards (i.e., uncertain rewards) are well suited to examine risk-taking in experimental settings. Therefore, Chapter 2 systematically reviews the literature on risky behavior in gambling tasks in individuals with ADHD. Studies on reward sensitivity in ADHD have predominantly made use of tangible rewards (e.g., money and presents). However, social rewards (e.g., praise, smile, and cooperation) are common rewards in daily life. Moreover, individuals with ADHD show difficulties in social functioning. Chapter 3, therefore, provides a systematic literature review on social reward processing in individuals with ADHD.

The second part of this thesis focuses on educational approaches of reward sensitivity in ADHD (Chapter 5 and 6). The interim Chapter 4 discusses the role of motivation in educational outcomes in students with ADHD. Considering that motivational deficiencies are likely to contribute to the educational difficulties of students with ADHD (see Chapter 4), Chapter 5 describes a meta-analytic review study on the effectiveness of classroom interventions (including reward-based interventions) for reducing task-irrelevant behaviors in students with symptoms of ADHD. It is important to apply these evidence-based classroom interventions in school practice. Therefore, Chapter 6 consists of a survey study among general education teachers in the Netherlands. This study examines teachers’ experiences with evidence-based classroom interventions (including reward-based interventions) for students with symptoms of ADHD.

The following **research questions** have been formulated:

1. Do individuals with ADHD demonstrate altered sensitivity to probabilistic rewards in gambling tasks?
2. Do individuals with ADHD demonstrate altered sensitivity to social rewards?
3. How effective are classroom interventions (including reward-based interventions) for reducing task-irrelevant behaviors in students with symptoms of ADHD?

4. What are teachers’ experiences with evidence-based classroom interventions (including reward-based interventions) for students with symptoms of ADHD?

To answer the first three research questions, systematic literature reviews have been performed. A systematic review provides an overview of the methodologies and findings of previous research, and therefore are valuable sources to answer research questions, determine the current state of research, and suggest directions for future research. Integrating evidence from several studies results in a more reliable conclusion than interpreting single studies. A specific type of systematic review is meta-analysis, which is a statistical procedure for combining data from multiple studies. Meta-analyses provide a more precise estimate of a treatment effect and may explain heterogeneity between individual studies (Tak, Meijer, Manoharan, de Jonge, & Rosmalen, 2010). Systematic (meta-analytic) reviews are often the foundation of evidence-based practice and therefore of particular clinical importance.