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"Changed behavioral dynamics in ADHD-C, but not in ADHD-PI groups"

Ketil Melås

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Summary

Attention-deficit/hyperactivity disorder (ADHD) is characterized by developmentally inappropriate levels of inattention, impulsiveness and hyperactivity. The dynamic developmental theory of ADHD (DDT) suggests that altered effects of reinforcement combined with a deficient extinction may be the main mechanisms for the development of the various symptoms observed in ADHD. Due to the combined effect of a shorter and steeper delay-of-reinforcement gradient and deficient extinction, the DDT predicts that it takes more time to build chains of predictable behavior in children with ADHD compared to other children. The primary aim of this study was to explore this prediction in a group with ADHD-C and ADHD-PI compared to a group of children with other psychiatric problems.

The present study is part of a collaborative study with Rosemary Tannock at the Hospital for Sick Children in Toronto, Canada.

The sample consisted of 45 children aged 9-12 years, 31 boys and 14 girls. These children were divided into four groups based on DSM-IV diagnoses: ADHD-C, ADHD-PI, ADHD-HI, and a control group of children with other psychiatric problems. The children completed a computerized game-like task called "Feed the Animal". Mouse clicks within a specified area were associated with reinforcement. Behavior was measured as responses by the computer mouse under two reinforcement contingencies. Reinforcers were set up according to a random interval schedule (RI 15s) and a random ratio schedule (RR 5). Autocorrelations of consecutive responses was analyzed to investigate predictability of responding. Low predictability in responding would imply greater behavioral variability.

We found that the responding in the ADHD-combined group was significantly less predictable than the two other groups during infrequent reinforcement (RI 15s). Thus, the findings that the children with ADHD-combined have more difficulties learning long sequences of behavior than the children with ADHD-PI and psychiatric controls, support the prediction from DDT that there may be different underlying mechanisms in children with ADHD-C and ADHD-PI.

The testing and collection of data was conducted by Rosemary Tannock and Anne-Claude Bedard at the Hospital for Sick Children in Toronto, Canada.

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Abstract: Attention-deficit/hyperactivity disorder (ADHD) is characterized by developmentally inappropriate, cross-situational, impairing levels of inattention, impulsiveness and hyperactivity. Altered effects of reinforcement combined with a deficient extinction have been proposed to be the main mechanisms for the development of the various symptoms observed in ADHD, as suggested by the dynamic developmental theory of ADHD (DDT). Due to the combined effect of a shorter and steeper delay-of-reinforcement gradient and deficient extinction, the DDT predicts that children with ADHD will have more difficulties acquiring chains of behavior than other children. Shorter chains of behavior are observed as more variable and unpredictable behavior. In the present study we explored this prediction in a group of children with ADHD-combined and ADHD-primarily inattentive compared to a group of children with other psychiatric problems. A sample of 45 children completed a computerized game-like task requiring responses by the computer mouse. Reinforcers were set up according to a random interval schedule (RI 15s) and a random ratio schedule (RR 5). Autocorrelations of consecutive responses was analyzed to investigate predictability of responding. Low predictability in responding would imply greater behavioral variability. We found that the responding in the ADHD-combined group was significantly less predictable than the two other groups during infrequent reinforcement (RI 15s). No significant group difference was found during frequent reinforcement (RR 5). Thus, the findings that the children with ADHD-combined have more difficulties learning long sequences of behavior than the children with ADHD-PI and psychiatric controls, support the suggestion from DDT that there may by different underlying mechanisms for ADHD-C and ADHD-PI.

1. Introduction

1.1. Epidemiology

Attention deficit-hyperactivity disorder (ADHD) (American Psychiatric Association, 2000) is one of the most common childhood psychiatric disorders, affecting approximately 2 - 5% of the grade-school population (Swanson et al., 1998b; Taylor, 1998), although the estimates are found to vary between 4% and 19% depending upon the exact criteria used (Taylor et al., 1998). The prevalence of Hyperkinetic Disorder (HKD) used by the ICD-10 (World Health Organization, 1993) is estimated to be 1 – 2 % (Taylor et al., 1998; Taylor, 1998; Swanson et al., 1998b). The reason why the prevalence estimates of ADHD differs greatly between studies may not be that the differences between populations actually are so great, but may partly be because of the different diagnostic systems used, diagnostic measures used, sampling methods, number of informants used, handling of comorbidity, age of population, country, and the nature of the population studied (Boyle et al., 1996). The disorder should by definition have an onset before the age of 7 (Taylor et al., 1998), but this is not always the case, especially when it comes to the primarily inattentive type (Applegate et al., 1997). ADHD is more common in boys than in girls, especially in childhood, with the sex ratio estimated to be 4:1 in epidemiological samples, and 9:1 in clinical samples (Cantwell, 1996). Such estimates may vary depending on the type (i.e., the Predominantly Inattentive type may have a gender ratio that is less pronounced) and setting (i.e., clinic-referred children are more likely to be male) (American Psychiatric Association, 2000). ADHD is considered a risk factor for later delinquency, substance abuse and personality disorders (Taylor, 1998). Of the individuals diagnosed with ADHD, the majority of these continue to have psychiatric and social problems in adolescence and young adulthood (Cantwell, 1996).

1.2. Symptoms and diagnosis

The understanding and diagnosis of what today is called ADHD has undergone substantial changes over the years and across the various revisions of diagnostic systems used. No biological marker has yet been identified for ADHD, thus the diagnosis is based strictly on descriptions of behavioral symptoms. The diagnostic system currently in use in the US is the Diagnostic and Statistical Manual of Mental disorders fourth edition, the DSM-IV (American Psychiatric Association, 2000). In Europe, the International Classification of Diseases tenth edition (ICD-10) is used (World Health Organization, 1993). These systems have a somewhat different definition of what is called ADHD in DSM-IV, but have in the most recent revisions become more alike in terms of the diagnostic criteria pertaining to ADHD.

DSM-IV defines ADHD in terms of persisting, developmentally inappropriate, cross-situational, impairing levels of inattention, impulsiveness and hyperactivity. Although many individuals present with symptoms of both inattention and hyperactivity-impulsivity, there are individuals in whom one or the other pattern is predominant. Following this, DSM-IV divides ADHD into 3 different subtypes, namely ADHD Predominantly Inattentive type (ADHD-PI), ADHD Predominantly Hyperactive-Impulsive type (ADHD-HI), and ADHD Combined type (ADHD-C). The appropriate subtype should be indicated based on the predominant symptom pattern for the last 6 months (American Psychiatric Association, 2000).

The ICD-10 has a somewhat narrower definition of what is referred to as Hyperkinetic Disorder than the ADHD diagnosis in DSM-IV. It appears that all the cases referred to as hyperkinetic disorder falls under the criteria of ADHD, but not the other way around. In the ICD-10, all three problems of attention, hyperactivity and impulsiveness should be present for the diagnosis, and it is required that the symptoms are manifest across different situations. In addition, the presence of another disorder like anxiety is in itself an exclusion criterion. These main symptoms have a considerable overlap, but impulsivity is increasingly seen as the symptom with greatest significance (Taylor et al., 1998).

The various symptoms are found to be context dependent in that they are variously manifested in different situations. Symptoms may be minimal or absent when the individuals are in novel situations, are receiving frequent reinforcers for appropriate behavior, are under close supervision, are engaged in especially interesting activities, or are in a one-to-one situation (American Psychiatric Association, 2000).

1.2.1. Attention

According to DSM-IV which divides ADHD into subtypes, it's possible to have ADHD without being inattentive (ADHD-HI). ICD-10 on the other hand requires inattentiveness for the diagnosis of Hyperkinetic disorder (HKD) (Taylor, 1998). The presence of inattentiveness is described as problems in sustaining attention, distractibility, frequent shifts between activities, and an apparent inability to follow instructions. Tasks that require sustained mental effort are experienced as unpleasant and markedly aversive, and often lead to an avoidance of such activities. It is a criterion that this avoidance is not better accounted for by an oppositional attitude, but is due to the person's difficulties with attention (American Psychiatric Association, 2000).

1.2.2. Hyperactivity

Hyperactivity is in children with ADHD often expressed by fidgeting with hands or feet, squirming in the seat, running or climbing excessively in situations where it is inappropriate. Hyperactivity is found to vary with the individual's age and developmental level, and caution must be taken in diagnosing young children (American Psychiatric Association, 2000).

1.2.3. Impulsivity

Impulsivity is described as impatience, difficulty in delaying responses, blurting out answers before questions have been completed, difficulties in awaiting turn, and interrupting or intruding others (American Psychiatric Association, 2000).

1.3. Comorbidity

One of the factors that complicate the prognosis and diagnostic process of children with ADHD is the fact that many of the individuals with ADHD also have additional psychiatric disorders, called comorbid disorders. The estimates for this vary according to the diagnostic criteria used to define ADHD (DSM-IV vs. ICD-10), the criteria used to define the comorbid disorder, and the sample under study. In general, oppositional/defiant disorder (ODD) is observed in 35-50% of cases, conduct disorder (CD) in 25%, depressive disorder in 15%, and anxiety disorder in 25% (Jensen et al., 1997; Kuhne et al., 1997).

1.4. Treatment

The most common treatment used with ADHD today is psychomotor stimulant medication and behavioral therapy, and combination of these are considered to be the most effective treatment of ADHD (Conners et al., 2001). Stimulant medication like methylphenidate and amphetamines are found to have an effect on the release and inhibition of reuptake of catecholamines, especially pertaining to dopamine (Swanson et al., 1998b). The use of psychomotor stimulants like methylphenidate and d-amphetamine has raised concern among clinicians and the public that it may represent a risk-factor for later substance abuse. Studies addressing this concern and exploring the effects of pharmacotherapy in ADHD have shown that they contrary to the common belief reduces the risk for later substance abuse (Biederman et al., 1999). Although we to date do not have a definitive answer to how psychomotor stimulants work, it has been shown to ameliorate the core symptoms in ADHD: Improve attention, and reducing hyperactivity, impulsivity, and restlessness in children with ADHD. These therapeutic effect of stimulants have earlier been seen as paradoxical, but similar behavioral effects appear to exist in normal children also (Rapoport & Inoff-Germain, 2002). Stimulant medication is reported to have an clinical effect on approximately 80% of patients with ADHD and HKD (Swanson et al., 1998b).

1.5. Etiology

Several lines of research have yielded important information about the etiology of ADHD. Studies of twins (monozygotic vs. dizygotic), adoption studies, and family studies strongly support a genetic contribution in ADHD. Some have found heritability in ADHD to be approximately 80% (Taylor et al., 1998), but the estimates are found to vary between 55% to 92% (Cantwell, 1996). Concordance has been found to be 51% in monozygotic twins and 33% in dizygotic twins (Goodman, 1989). Adoption studies show that biological parents of individuals with ADHD are more likely to exhibit ADHD or related disorders than are adoptive parents (van den Oord et al., 1994). ADHD is also shown to aggregate in families, which suggests a genetic contribution (Swanson et al., 1998b).

Even though there is a strong genetic component in ADHD, no single gene has been identified as being the basis of ADHD. It is likely that there is a polygenetic and multi-determinant etiology of ADHD, and that the genetic contribution arises from polymorphisms, not single genes, and that these polymorphisms in turn interact with the environment to create the symptoms and functional impairments observed in ADHD (Sagvolden et al., 2005). Molecular genetics have proposed several candidate genes linked to ADHD, and these are mostly associated with neuromodulatory functions. Many of these studies have focused on various dopamine genes, among others the genes coding for DAT1 dopamine transporter and the DRD4 dopamine receptor (See Sagvolden et al., 2005 for a review).

Through the use of neuroimaging techniques, several neuroanatomical correlates to ADHD have been proposed. Two brain regions that have been identified to be smaller in some individuals with ADHD compared to control groups, are the frontal lobes and the basal ganglia (Swanson et al., 1998a).

Although psychosocial factors are not thought to play a primary etiological role (Cantwell, 1996), it seems clear that the interaction with such environmental factors play a crucial role in determining the course of ADHD (Sagvolden et al., 2005). A range of environmental factors is found to be associated with the development of hyperactivity. Examples of this are fetal exposure to alcohol and benzodiazepines during pregnancy, and maternal smoking among other factors (Taylor et al., 1998).

1.6. Theories of ADHD

The search for an explanation of the symptoms in ADHD has resulted in a wide range of models and theories, and it is beyond the scope of this paper to review all of them. Many of these models have focused on behavioral and cognitive mechanisms suggested to be linked to the behavioral symptoms commonly observed in ADHD. Others have tried to create more comprehensive theoretical accounts, although none of these have so far been able to fully account for all research findings or all cases of ADHD (Nigg, 2005).

1.6.1. Barkley and inhibition

One of these theoretical accounts is a model that seeks to explain the behavioral characteristics in ADHD in terms of deficient behavioral inhibition (Barkley, 1997). This deficit in behavioral inhibition is thought to be important for the effective execution of four executive functions: 1) working memory; 2) self-regulation of affect, motivation and arousal; 3) internalization of speech; and 4) reconstitution (behavioral analysis and synthesis). The model predicts that ADHD should be associated with secondary impairments in these 4 executive abilities, like decreased control of motor behavior and self-directed action. Inhibitory behavioral control refers to the ability to withhold a planned response; to interrupt a response that has been started, which thereby permits a delay in the decision to respond; or the ability to resist distraction or disruption by competing events. The ability to inhibit a response is according to Barkley a prerequisite for self-regulation, which itself is considered an executive function. Deficits in behavioral inhibition may then be a way of describing what is commonly referred to as impulsivity in ADHD. Because of this deficit, the behavior in ADHD is hypothesized to be more controlled by the immediate context and its consequences than the behavior of other children. On a behavioral level, he proposes that children with ADHD will have more problems than normal children in building longer chains of behavior to achieve future goals and consequences when there is an absence of immediate reinforcement, but that this not will be the case when frequent reinforcement is available. Poor sustained attention resulting from poor inhibition is thought to account for such deficient effects of reinforcement (Barkley, 1997).

1.6.2. Sergeant and cognitive-energetics model

It has been argued that the hypothesized inhibition deficit claimed to account for the performances of children with ADHD on numerous tasks is an oversimplification with regard to differentiating their performances from the performances of others without an ADHD diagnosis (Sergeant, 2000). Children with an ODD or CD diagnosis also display deficits in inhibition (Oosterlaan et al., 1998). Sergeant (2000) proposes an alternative explanation; a cognitive-energetics model (CEM). This model suggests that children with ADHD suffer from a nonoptimal energetic state. It is built upon the assumption that information processing is influenced by both computational (process) factors and state factors such as effort, arousal and activation pools. The given state of the arousal and activation pool is controlled by effort, which refers to the energy necessary to meet the demands of a task. Reinforcement contingencies are presumed to have their influence on this pool, and thus have an effect on the performance on cognitive tasks. In this model it is suggested that the deficits in inhibition of responses among children with ADHD, measured by tasks like the go/no-go task, stop-signal task and the change task, is modulated by an inability to adjust their state and a deficient allocation of energy to the task at hand.

1.6.3. Sonuga-Barke and delay aversion

Compared to their normally developing peers, children with ADHD seem to respond differently to reinforcers. They seem unusually sensitive to immediate reinforcement and have difficulties with delayed reinforcers. Experiments and observations have shown that they are more likely to respond for a small reinforcer that comes immediately, rather than a larger reinforcer that comes after a delay (Sonuga-Barke et al., 1992). It has been suggested that this reflects a deficit in inhibition of responses (Taylor, 1998), but as Sonuga-Barke et al. (1992) found when the maximum amount of reinforcers or the maximum amount of time to complete the task was predetermined, the children was able to choose the large delayed reinforcer over the immediate smaller reinforcer. This shows that their problem was not necessarily that they were not unable to inhibit responses. They suggest that the decisions to not wait for reinforcers are more about aversion to delay than deficient inhibition. In contrast to this, (Tripp & Alsop, 2001) found that children with ADHD preferred immediate over delayed reinforcers irrespective of whether the overall delay was similar or not.

In a study that explored the ecological validity of delay aversion and response inhibition as measures of impulsivity in ADHD, they concluded that both processes were in play, but that they worked independently (Solanto et al., 2001). (Sonuga-Barke, 2002) has suggested a dual-pathway model to account for the symptoms in ADHD in terms of two separate dysfunctional brain mechanisms; one associated with diminished inhibitory control and the other with increased reinforcement sensitivity. This model predicts that delayed and noncontinuous reinforcement will result in a diminished task performance for delay aversive children with ADHD, and that immediate reinforcement are preferred over delayed ones.

1.6.4. The Dynamic developmental theory of ADHD (DDT)

Altered effects of reinforcement combined with a deficient extinction in children with ADHD have been proposed to be the main mechanisms for the development of the various symptoms observed in ADHD (Johansen et al., 2002; Sagvolden et al., 2005).

1.6.4.1. Reinforcement

Reinforcement is a prerequisite for both the learning and maintenance of behavior (Catania, 1998). What is learned is the relation between some behavior and the consequences of that behavior. If the behavior increases when it has certain consequences, we say that the behavior in reinforced. Through differential reinforcement, certain classes of responses can be reinforced, and thus make the likelihood for the occurrence of more responses of the same response class increase given the same consequences. Catania (1998) differentiates between nominal classes (the behavior that is reinforced) and functional classes (the behavior generated by reinforcement) of responses. The process of differentiation makes the responses emitted closely conform to the class of reinforced responses, and is the process which gradually selects behavior and makes it more probable.

1.6.4.2. The delay gradient

Delay of reinforcement is a common characteristic of various reinforcement schedules. Studies on effects of reinforcement using different reinforcement schedules have shown that reinforcement has a retroactive effect on the responses preceding the reinforcer. The effect of the reinforcer on the preceding responses wanes as function of time from the reinforcer, thus it has a stronger effect on the responses immediately preceding the reinforcer than earlier responses. This has been graphically illustrated in the reinforcement gradient (Dews, 1962). The effects of reinforcement on responses that precede the one that produces a reinforcer are not restricted to responses of a single operant class (Catania, 1998).

An altered reactivity to reinforcement and deficient extinction has been suggested as the core of the problem in ADHD. Sagvolden et al. (2005) offered a dynamic developmental theory of ADHD (DDT) where they link neurobiological and genetic correlates of ADHD with behavioral symptoms observed in ADHD. Their primary focus has been on dopamine dysfunction and the hypothesis that altered dopaminergic function plays a pivotal role by failing to modulate nondopaminergic signal transmission appropriately (primarily glutamate and GABA). Dopamine hypofunction is suggested to produce a narrower time window for associating preceding stimuli, behavior, and its consequences. This proposed altered reinforcement mechanism in children with ADHD may be illustrated by the delay-of-reinforcement gradient (Fig. 1), where it is suggested that individuals with ADHD have a shorter and steepened delay gradient. The delay-of-reinforcement gradient is based on behavioral observations and analyses, and should not be used explanatory, but the DDT is also based on neurobiological evidence and knowledge of how reinforcement processes are linked to dopamine function. This evidence of dopamine dysfunction in ADHD combined with findings on how dopamine modulates neuronal activity and plasticity is an explanation of why effects of reinforcers are altered in ADHD and how dopamine dysfunction translates into what in behavioral terms can be described as a steepened delay-of-reinforcement gradient. It is assumed that both hyperactivity and behavioral variability seen in ADHD is acquired and maintained by a combined effect of reinforced behavior and a deficient extinction of earlier reinforced behavior (Johansen et al., 2002; Sagvolden et al., 2005) (Fig. 2).

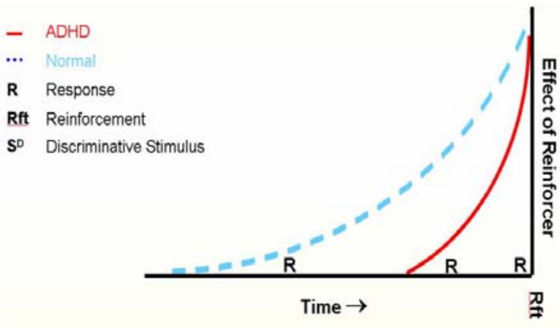

Figure 1. Delay-of-reinforcement gradients. A reinforcer is more effective when there is a short delay between response and reinforcer than when there is a long delay. The gradient may be shorter and steepened in children with ADHD (adapted from Sagvolden et al., 2005).

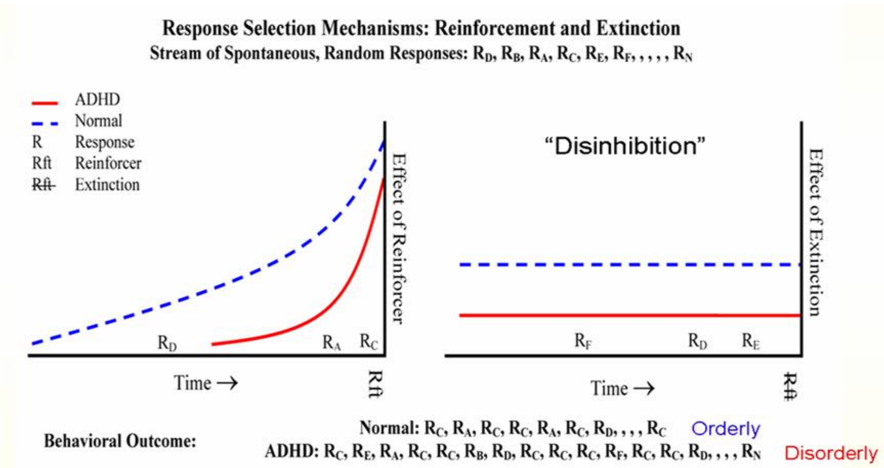

Figure 2. The selection of responses by reinforcement and extinction. Left: Delay-of-reinforcement gradients. Right: Due to a suggested deficient extinction process, the pruning of previous but no longer reinforced responses is less effective in children with ADHD than normally (adapted from Sagvolden et al., 2005).

1.6.4.3. ADHD symptoms caused by an altered delay gradient

The hypothesis of altered reinforcement mechanisms has been explored in a study of children with ADHD compared with a normal comparison group (Sagvolden et al., 1998). They analyzed the behavior during a multiple fixed interval extinction schedule (FI 30s - EXT 2min). The results showed that the children with ADHD gradually developed hyperactive behavior defined as bursts of responses with short interreponse times (IRTs; time between two consecutive responses) during both schedules, while the comparison group mainly exhibited long IRTs. The authors suggest that this might be a key component of the behavior commonly described as impulsiveness. Responding during extinction in the ADHD group is by the authors suggested to be a sign of poor stimulus control observed as problems with sustained attention. The results also showed that the total number of responses in general was higher and the response patterns more variable in the ADHD group than in the comparison group. The main difference in number of responses was that the children with ADHD successively increased their responding throughout the session, while the comparison group did not. This is in line with the DDT (Sagvolden et al., 2005) which predicts responding to be at a normal level in novel situations.

1.6.4.4. Intra-individual variability in ADHD

Behavioral variability has been reported repeatedly in ADHD performance, and has been suggested to be a key characteristic of an endophenotype of ADHD (Castellanos et al., 2005). Behavioral variability is also a prerequisite for learning, in that learning is the gradual selection of some behavior over others through the process of reinforcement. For a selection between various behaviors to take place, variability in behavior is necessary (Catania, 1998).

Two recent studies explored behavioral variability among Norwegian and South African children with ADHD by using a computerized game-like free-operant task (Aase & Sagvolden, 2005; Aase et al., 2006). It is called a free-operant task because the organism is free to emit the response at any time rather than waiting for a new trial, and operant because the response operates on the environment (Catania, 1998). Results from the Norwegian children with ADHD showed that they acquired significantly shorter response sequences than the comparison group on measures related to response location, while none of the groups showed any predictability in response timing. Predictability of response location and timing were measured in terms of variance explained by autocorrelations. The results showed significantly lower predictability of responding in ADHD than in non-ADHD groups.
The authors hypothesize that problems with learning long behavioral sequences may be a basic problem in ADHD that may ultimately lead to deficient development of verbally governed behavior and self control (Aase & Sagvolden, 2005). The same task was used in a follow-up study of South African children from 7 ethnic groups (Aase et al., 2006). The results were in general comparable to the ones found in the Norwegian population. In this study, the children with ADHD were divided into subgroups according to the ones in DSM-IV

(ADHD-C, ADHD-PI, and ADHD-HI). The ADHD-C group showed significantly lower predictability than the non-ADHD group, with intermediate predictability in the ADHD-HI and the ADHD-PI groups on response location but not response timing. Taken together the results from these two studies support the notion that ADHD-related variability is an important characteristic of ADHD behavior. By replicating the findings from the Norwegian study, the conclusion that ADHD is a basic neurobehavioral disorder is also supported (Aase et al., 2006).

Using the same game like task as in the Norwegian and South African studies, increased behavioral variability and deficient sustained attention was also found in another group of children with ADHD (Aase & Sagvolden, 2006). The children were in this study reinforced according to two alternating variable interval schedules (VI 2s and VI 20s). A significant difference was found between the ADHD group and comparison group on sustained attention and variability, but this only occurred under the contingencies of infrequent reinforcement, and not during frequent reinforcement.

1.6.4.5. Building chains of behavior

Due to a steeper and shorter delay gradient, reinforcers are according to DDT predicted to have less effect on the behavior of children with ADHD compared to normal controls. Combined with a deficient extinction of previously reinforced responses, it is predicted that children ADHD would have more difficulties building chains of behavior than others. Given a short and steepened delay gradient, only the behavioral sequences that occur within the restricted time window will be reinforced as predicted by the DDT. The implications of this may be substantial in that the establishment of serial ordering of behavioral units and the ability of building longer chains of behavior is a prerequisite for learning more complex behavior (Lashley, 1951). Shorter chains of behavior are observed as more variable and unpredictable behavior (Sagvolden et al., 2005).

In the present study two different reinforcement schedules were used. Reinforcers were delivered according to a random interval (RI 15s) schedule and a random ratio (RR 5) schedule. In a random interval schedule the delivery of a reinforcer do not depend on number of responses, but it reinforces a single response that occurs after a specified time has elapsed. A random ratio schedule randomly selects some fraction of responses for reinforcement (Catania, 1998). Thus, a pause in responding increases the probability of a reinforcer in RI schedules, while a new response with a short IRT increases the density of reinforcement in RR schedules (Fig. 3). Thus, RI schedules should enhance behavioral differences between normal and steepened delay gradients while RR schedules should not produce as pronounced group effects if the delay gradients start at approximately the same level. Effects of frequent vs. infrequent reinforcement on behavioral predictability were analyzed.

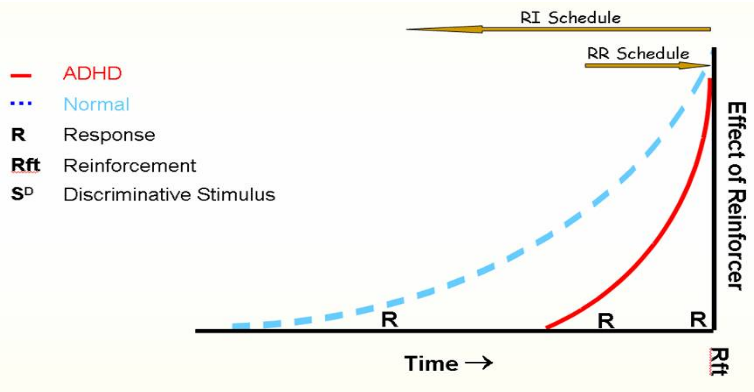

Figure 3. Differential schedule effects on responding. The difference in reinforcer effect between the two gradients is larger with long IRTs than with short. A pause in responding increases the probability of a reinforcer in RI schedules, while a new response with a short IRT increases the density of reinforcement in RR schedules (adapted from Sagvolden, et al., 2005).

1.7. Study aims and operationalizations

The DDT predicts that it takes more time to build chains of predictable behavior in children with ADHD compared to other children due to a combined effect of a steepened and shorter delay gradient and deficient extinction (Johansen et al., 2002; Sagvolden et al., 2005). Thus, the primary aim of this study was to explore this prediction in a group with ADHD-C and ADHD-PI compared to a group of children with other psychiatric problems.

1.7.1 Control measures

A shorter and steepened delay gradient predicts bursts of responding with short IRTs, since only consecutive responses with short interresponse time will be reinforced. The long IRT between R_D and R_C in figure 2 (left) will only be reinforced by a normal delay gradient, while the IRT between R_A and R_C will be reinforced by both gradients. Thus, impulsiveness is usually operationalized in terms of bursts of responding with short interresponse times (IRTs)(Aase & Sagvolden, 2005; Aase et al., 2006). In the present study however, random interval and random ratio schedules were used. These schedules produce a relatively stable response output without temporal patterning. Thus, no patterning of IRTs was predicted for any of the groups in the present study. Such a result would be in accordance with previous research from the present group (Aase & Sagvolden, 2005; Aase et al., 2006).

Autocorrelations of consecutive interresponse times was analyzed to explore temporal patterns of responding.

The DDT predicts that a dysfunctional nigro-striatal dopamine branch would result in a range of extrapyramidal symptoms like clumsiness, poor motor control, longer and more variable reaction times, poor response timing, poor handwriting, and poor correlation of the activity of different body parts (Sagvolden et al., 2005). Motor control was measured as predictability of movements using autocorrelations between consecutive responses during the reinforcement situation.

Hyperactivity is commonly seen in children with ADHD as fidgeting with hands or feet, squirming in the seat, running or climbing excessively in situations where it is inappropriate (American Psychiatric Association, 2000). The DDT predicts that in addition to leading to increased behavioral variability, a deficient extinction process will result in an increased number of responses. Hyperactivity was measured as number of responses, i.e. clicks on the mouse.

2. Methods

2.1. Subjects

The subjects in this study were recruited from The Hospital for Sick Children in Toronto, Canada. They consisted of 45 children aged 6-12 years, 31 boys and 14 girls. On the basis of diagnosis, the children were divided into four groups, namely “ADHD-HI” (n=1), “ADHD-C” (n=26), “ADHD-PI” (n=8) and “Psychiatric controls” (n=10). The group ADHD-HI was left out of the further analysis because we only had data from one child with ADHD-HI. The psychiatric control children were a heterogeneous group consisting of children with various psychiatric diagnoses like disruptive behavioral disorders (ODD and CD), anxiety-disorders, learning disorders, and adjustment disorders. The children in this study have been thoroughly diagnosed according to the DSM-IV. Clinical diagnoses used in the data analyses are based on judgements made by a clinical team, taking into account both scores from interviews and rating scales, as well as global clinical impressions. Several of the children with an ADHD diagnosis also presented comorbid diagnoses. The present study is a collaborative study with Rosemary Tannock, and the testing was conducted by Rosemary Tannock and Anne-Claude Bedard at The Hospital for Sick Children in Toronto, Canada.

2.2. Procedure

2.2.1. Reinforcement task

The task in this study was designed as a computer game called “Feed the Animal” (FTA). This program is designed for testing children aged 4-13 years (approximately). It measures behavior controlled by different reinforcement schedules. Behavior was measured as mouse clicks during the stimulus situation, and as movement of mouse during the reinforcement situation (coordinates of mouse trajectory and time of movement).

2.2.2. Stimulus situation

The task started with a scene on the screen: An open field with a few trees in the background. In the front there was a bench with a barrel on it. The barrel contained animal food (Fig. 4). Mouse clicks within a certain area (on the food barrel) gave a certain feedback (sound).

Figure 4. Scenery during the stimulus situation.

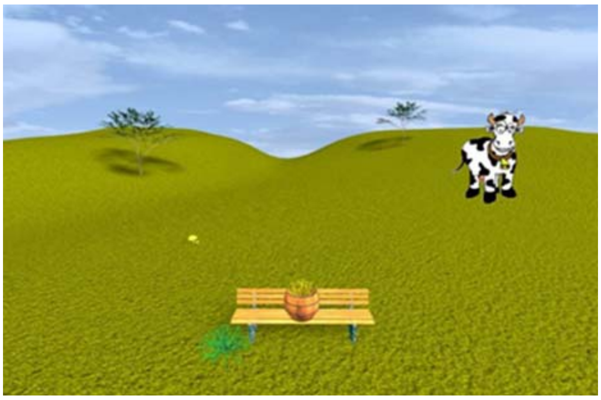

Figure 5. Scenery during the feeding situation.

2.2.3. Reinforcement

Whenever a reinforcer was scheduled, the next correct response, a mouse click within the defined area, resulted in an animal popping up on the scene. The animal would just be there, standing still, at some distance from the food barrel (Fig. 5). The animal randomly showed up at either right or left side of the screen. The hand then changes to a bunt of food. Moving the mouse resulted in moving the food. The child could move the food from the barrel over to the animal. The animal ate the food if the child hit its mouth correctly. The mouth area was defined in the program as a small area and equal in size every time. Given that the child hit the mouth correctly, the animal did something funny (jumped, exploded, ran) accompanied by a sound. There was no time limit for feeding the animal. After this the animal disappeared and the hand could again be used for calling the animal by clicking the mouse on the barrel. What kind of animal which appeared and what it did varied from one time to the next, so that it did not become repetitious.

2.2.4. Game process

The game started with a learning phase (shaping), when the child practiced the task. The child was just told to use the mouse to move the cursor and click the buttons. Clicks within a certain area around the barrel were reinforced, i.e. they resulted in a little sound. The threshold for getting a sound was raised for every response, so that the child would click closer and closer to the barrel. Each click on the barrel resulted in a reinforcement situation. After 5 consecutive correct responses, the task was assumedly learned, and the program moved on to the test phase. The number of responses in the learning phase was recorded.

2.2.5. Test phase

The pre-specified contingencies were set to operate and start, without notice, just after the last reinforcer in the learning phase. The game then ran to its end, where the scenery crumbled and turned black.

2.2.6. Data recording

From this we got two data files, one with coordinates of responses during the reinforcement schedules and one with timing and coordinates of mouse trajectory during the feeding situation (measured in 50 ms intervals).

2.2.7. Instructions for the child

The only thing the children were told in advance of the testing was: "*This is a game you can play. Your task is to feed animals with your (nonpreferred) hand. You have to find out how to make the animals appear and how to feed them. The game will stop by itself*".

2.2.8. Instructions for the tester

The tester told the child that he or she would be busy doing some other work so that they would not be available for talking or further help. A record was made for what the child said and did during testing. The developers of the FTA program tells the tester to be sure to use a Logitech optical mouse, that both buttons work interchangeably during the game, the wheel is not in use, to use the highest double click speed setting for the mouse, regular pointer, no pointer shadow, maximum pointer speed, and to unselect “display pointer trails”. The screen resolution should be changed so that the picture fills the entire screen.

2.2.9. Pre-specified contingency parameters

Random Interval (RI): The first response after an interval that varies randomly around a specified arithmetic mean, in our case 15s, was reinforced. That is, the intervals in this condition would on average be 15s long. The interval time was not running while the child was feeding the animal.

Random Ratio (RR): A variable number of responses are required before a reinforcer is made available. The number of responses varies randomly around a specified mean, in our case the average was 5 responses.

2.3. Statistics

Data were formatted and autocorrelations were calculated by using SPSS 11.0 for Windows (SPSS, 2001). Statistica 7.1 program package (StatSoft, 2005) was used for the ANOVA and MANOVA.

3. Results

Outliers were removed from the analysis according to the rule that data points more than 2 SD outside the group mean for the different variables were replaced with -999 (missing). ADHD-related variability was defined as reduced predictability of consecutive responses. Autocorrelations between lags were used to analyze this predictability.

3.1. Response pattern during RI Schedule

This measure assessed where on the screen the children clicked during the RI schedule. During the RI schedule fast responding is not reinforced, rather the chances of getting a reinforcer increases by not clicking for a while. In the experiment this translates into where the children click on the screen in regard to the barrel. Predictable responding across lags would imply that behavior was ordered in sequences of similar distances between responses, specifically related to the centre of the barrel. Our analysis show that ADHD-C differs from both the ADHD-PI and the psychiatric controls when the RI schedule is in effect.

3.1.1. Horizontal movements

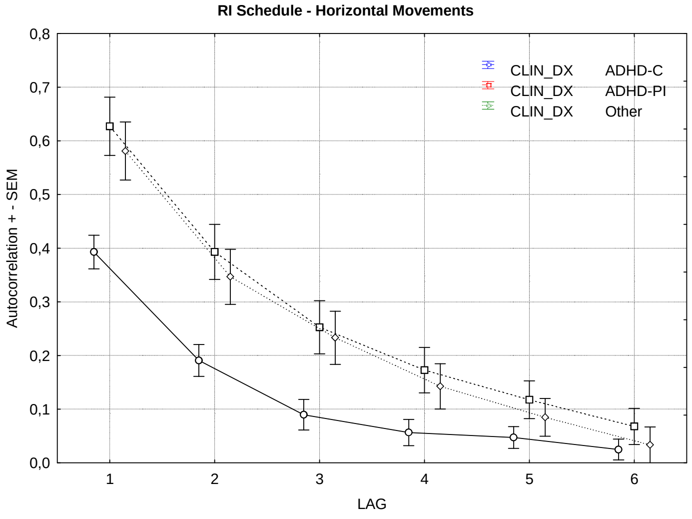

Figure 6. Autocorrelations of horizontal movements during the RI schedule by lag between responses.

Table 1. ANOVA of horizontal movements during the RI 15s schedule.

Effect	Repeated Measures Analysis of Variance (FTA Autocorr +- 2 SD.sta Sigma-restricted parameterization Effective hypothesis decomposition Exclude condition: child_id >55000 SS	Degr. of Freedom	MS	F	p
Intercept	7,425740	1	7,425740	125,5246	0,000000
CLIN_DX	0,759515	2	0,379757	6,4194	0,004528
Error	1,893044	32	0,059158		
LAG	4,501447	5	0,900289	173,0622	0,000000
LAG*CLIN_DX	0,224900	10	0,022490	4,3232	0,000023
Error	0,832338	160	0,005202		

Table 2. MANOVA of horizontal movements during the RI 15s schedule.

Effect	Multivariate tests for repeated measure: DV_1 (FTA Autocorr +- 2 SD.sta Sigma-restricted parameterization Effective hypothesis decomposition Exclude condition: child_id >55000 Test	Value	F	Effect df	Error df	p
LAG	Wilks	0,074830	69,23595	5	28	0,000000
LAG*CLIN_DX	Wilks	0,634064	1,43269	10	56	0,190268

On the measure of horizontal movements of the mouse, there was a significant main effect of Group $F(2,32)=6.42$, $p<0.005$; and Lag $F(5,28)=69.24$, $p<0.001$; but no significant interaction between group by lag $F(10,56)=1,43$, $p>0,15$ using MANOVA. This means that the responses of the ADHD-C group were significantly less predictable than both the ADHD-PI group and the psychiatric control group. There were no other statistically significant effects.

3.1.2. Vertical movements

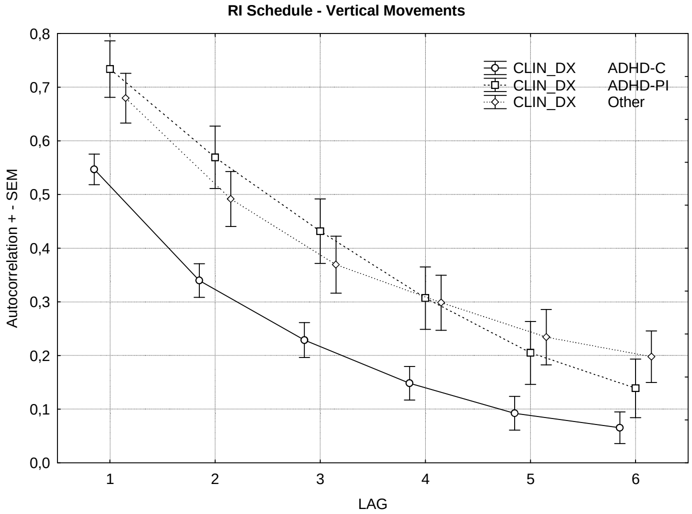

Figure 7. Autocorrelations of vertical movements during the RI schedule by lag between responses.

Table 3. ANOVA of vertical movements during the RI 15s schedule.

	Repeated Measures Analysis of Variance (FTA Autocorr +- 2 SD.sta Sigma-restricted parameterization Effective hypothesis decomposition Exclude condition: child_id >55000				
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	20,82173	1	20,82173	184,6172	0,000000
CLIN_DX	1,30316	2	0,65158	5,7773	0,006554
Error	4,17298	37	0,11278		
LAG	5,81859	5	1,16372	241,5145	0,000000
LAG*CLIN_DX	0,09754	10	0,00975	2,0243	0,033059
Error	0,89141	185	0,00482		

Table 4. MANOVA of vertical movements during the RI 15s schedule.

	Multivariate tests for repeated measure: DV_1 (FTA Autocorr +- 2 SD.sta Sigma-restricted parameterization Effective hypothesis decomposition Exclude condition: child_id >55000					
Effect	Test	Value	F	Effect df	Error df	p
LAG	Wilks	0,077746	78,29202	5	33	0,000000
LAG*CLIN_DX	Wilks	0,697340	1,30354	10	66	0,247160

Measures of vertical movements of the mouse, showed a significant main effect of Group $F(2,37)=5.78$, $p<0.01$; and Lag $F(5,33)=78.29$, $p<0.001$, but we found no significant interaction between Group by Lag using MANOVA $F(10,66)=1.3$, $p>0.2$.

These results are in concordance with the ones found on horizontal movements and show that the responding was more variable in the ADHD-C group than in both the ADHD-PI group and the psychiatric control group.

3.2. Response pattern during RR Schedule

When the RR schedule was in effect, we found that the significant group difference disappeared.

3.2.1. Horizontal movements

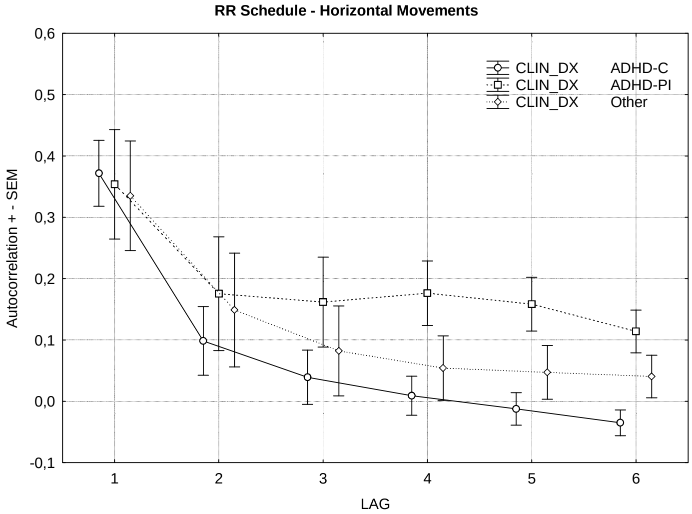

Figure 8. Autocorrelations of horizontal movements during the RR schedule by lag between responses.

Table 5. ANOVA of horizontal movements during the RR 5 schedule.

Effect	Repeated Measures Analysis of Variance (FTA Autocorr +- 2 SD.sta Sigma-restricted parameterization Effective hypothesis decomposition Exclude condition: child_id >55000				
	SS	Degr. of Freedom	MS	F	p
Intercept	3,032598	1	3,032598	22,26527	0,000037
CLIN_DX	0,439910	2	0,219955	1,61490	0,213380
Error	4,767107	35	0,136203		
LAG	2,020538	5	0,404108	23,34806	0,000000
LAG*CLIN_DX	0,171650	10	0,017165	0,99174	0,452432
Error	3,028895	175	0,017308		

Table 6. MANOVA of horizontal movements during the RR 5 schedule.

Effect	Multivariate tests for repeated measure: DV_1 (FTA Autocorr +- 2 SD.sta Sigma-restricted parameterization Effective hypothesis decomposition Exclude condition: child_id >55000					
	Test	Value	F	Effect df	Error df	p
LAG	Wilks	0,320827	13,12506	5	31	0,000001
LAG*CLIN_DX	Wilks	0,836344	0,57952	10	62	0,824458

In regard to horizontal movements during RR schedule, we found a significant main effect of Lag $F(5,31)=13.13$, $p<0.001$, but not for Group $F(2,35)=1.61$, $p>0.2$. No interaction effect of Group by Lag using MANOVA was found $F(10,62)=0.58$, $p>0.8$. The predictability of responding decreased similarly for all three groups across lags.

3.2.2. Vertical movements

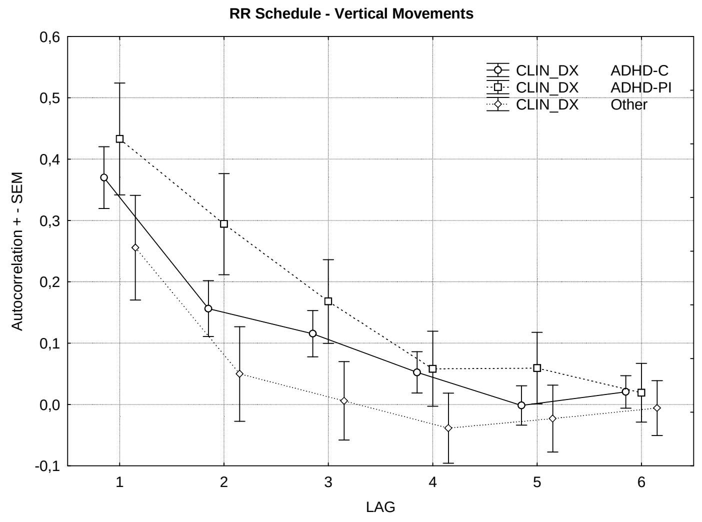

Figure 9. Autocorrelations of vertical movements during the RR schedule by lag between responses.

Table 7. ANOVA of vertical movements during the RR 5 schedule.

Effect	Repeated Measures Analysis of Variance (FTA Autocorr +- 2 SD.sta Sigma-restricted parameterization Effective hypothesis decomposition Exclude condition: child_id >55000				
	SS	Degr. of Freedom	MS	F	p
Intercept	2,117809	1	2,117809	16,10974	0,000300
CLIN_DX	0,401986	2	0,200993	1,52891	0,230899
Error	4,601149	35	0,131461		
LAG	2,578476	5	0,515695	35,35536	0,000000
LAG*CLIN_DX	0,142856	10	0,014286	0,97940	0,463108
Error	2,552560	175	0,014586		

Table 8. MANOVA of vertical movements during the RR 5 schedule.

Effect	Multivariate tests for repeated measure: DV_1 (FTA Autocorr +- 2 SD.sta Sigma-restricted parameterization Effective hypothesis decomposition Exclude condition: child_id >55000					
	Test	Value	F	Effect df	Error df	p
LAG	Wilks	0,306782	14,00982	5	31	0,000000
LAG*CLIN_DX	Wilks	0,748725	0,96524	10	62	0,482290

Not surprisingly we found comparable results in regard to vertical movements. In the same fashion as with horizontal movements there was a significant main effect of Lag $F(5,31)=14.01$, $p<0.001$, but no other statistically significant effects.

3.3. Temporal response patterns

The development of patterns in response timing was investigated by autocorrelating consecutive interresponse times (IRTs). We found no significant differences between groups using such an analysis.

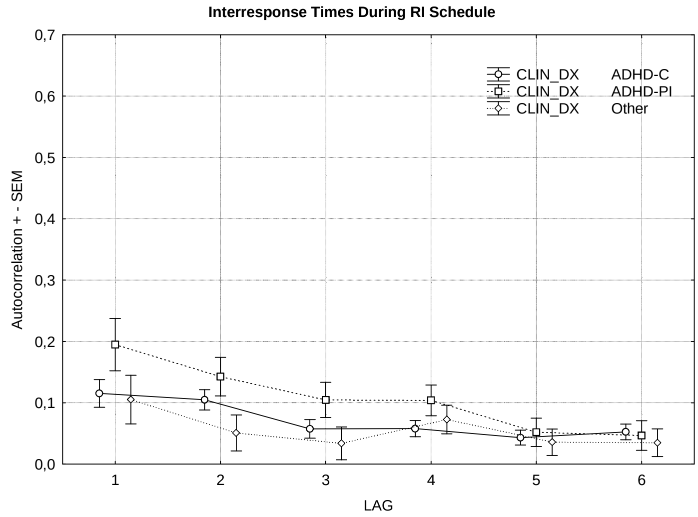

Figure 10. Autocorrelations of interreponse times during RI schedule by lag between IRTs.

Table 9. ANOVA of IRTs during the RR 5 schedule.

Effect	Repeated Measures Analysis of Variance (FTA Autocorr +- 2 SD.sta Sigma-restricted parameterization Effective hypothesis decomposition Exclude condition: child_id >55000				
	SS	Degr. of Freedom	MS	F	p
Intercept	1,074627	1	1,074627	54,43032	0,000000
CLIN_DX	0,063846	2	0,031923	1,61691	0,212224
Error	0,730497	37	0,019743		
LAG	0,191958	5	0,038392	10,84180	0,000000
LAG*CLIN_DX	0,042473	10	0,004247	1,19944	0,293838
Error	0,655097	185	0,003541		

3.4. Feeding

During the feeding situation the mouse trajectory was measured. Coordinates of the position of the cursor were recorded every 50 ms, and it was predicted that the behavior of the ADHD group would be more variable than the psychiatric control group. We found that the behavior during feeding did not discriminate at all between the groups.

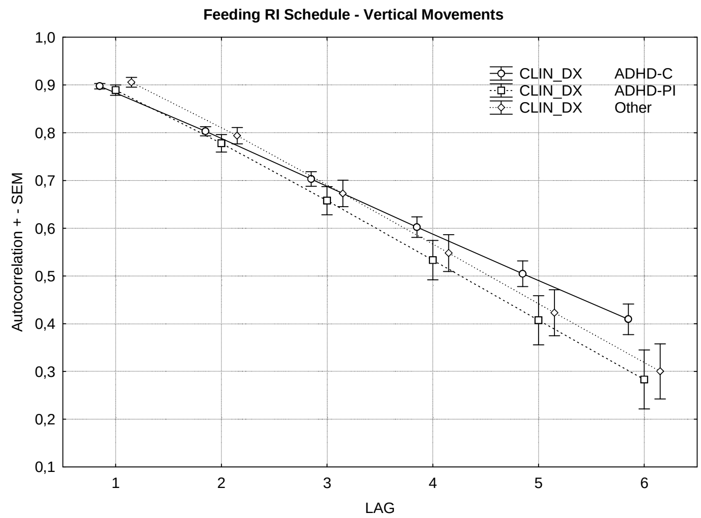

Figure 11. Autocorrelations of consecutive responses during feeding.

3.5 Total number of responses

We found no statistically significant differences between the groups in total numbers of responses during neither RI nor RR schedules.

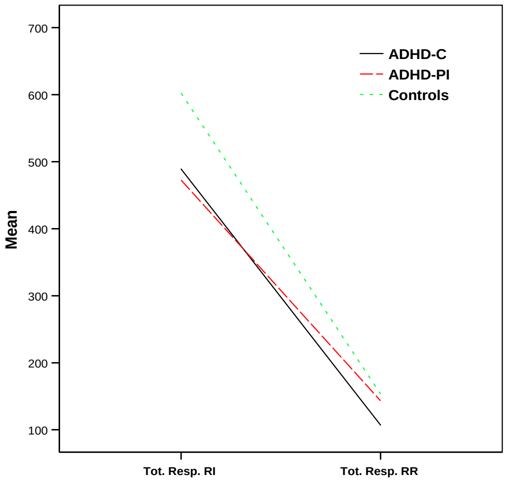

Figure 12. Total numbers of responses during the RI and RR schedules

4. Discussion

The present study investigated behavioral variability in a group of children with ADHD compared to a group consisting of children with other psychiatric disorders. The hypothesis tested was that a steeper and shorter delay-of-reinforcement gradient combined with deficient extinction of previously reinforced responses in children with ADHD would result in more difficulties with building behavioral sequences as predicted by the DDT (Sagvolden et al., 2005). To test this prediction, we used a game-like task called "Feed the Animal", and the reinforcement contingencies were set up according to a RI 15s schedule and a RR 5 schedule. Behavioral variability was operationalized as predictability of responding and measured by autocorrelations between consecutive responses. High predictability between responses would imply that by knowing one response we could reliably predict the next responses, and low predictability would imply greater behavioral variability. Autocorrelations were used because they allow a more detailed analysis of the dynamics of behavior. We explored consecutive responding in terms of spatial (horizontal and vertical movements) response patterns during RI, RR, and Feeding; and temporal patterning of responding (IRTs).

4.1. General findings

In general we found that the behavior of children with ADHD-C was more variable when the reinforcement schedule did not reinforce fast responding (random interval schedule), while there were no group difference when the schedule reinforces fast responding (random ratio schedule). Hyperactivity measured by total number of responses, showed no statistical differences between the groups in any condition. We found no group difference with regard to motor coordination as measured in the feeding situation. No temporal response patterns

4.2. Random interval vs. random ratio schedule

Differences in behavioral variability between the groups only occurred during the RI schedule, and not during the RR schedule. The ADHD-C group significantly differed in predictability of responding from both the ADHD-PI group and the psychiatric control group on both horizontal and vertical measures in the RI schedule. This suggests that reinforcement was less efficient in ADHD-C group compared to the psychiatric control groups during infrequent reinforcement. It is interesting to observe that the predictability of behavior in the ADHD-PI group is so similar to the behavior of the psychiatric control group. This supports the suggestion from both the DDT and others (Barkley, 1997; Taylor, 1998; Johansen et al., 2002; Sagvolden et al., 2005) that the attention problems observed in ADHD-PI and ADHD-C are quite different and that they may be two distinct disorders with separate etiologies and underlying mechanisms.

We found no significant differences in behavior between the groups during the RR schedule. This is in accordance with the DDT predicting that by presenting reinforcement frequently the children with ADHD may establish stimulus control in spite of a steeper and shorter delay gradient. One other explanation for the lack of differences between the groups could be that the RR schedule induces ADHD-like response pattern in the psychiatric control group, or that the time for testing was shorter in the RR schedule than the RI schedule.

Several studies have found greater variability in the behavior in children with ADHD during infrequent reinforcement, but that it normalizes under contingencies with frequent reinforcement (Aase & Sagvolden, 2006). The DDT predicts that when the time interval between reinforcers and responses becomes too long, it results in lack of stimulus control. This relation between discriminative stimulus, responses, and its consequences is what is described by the delay-of-reinforcement gradient (Fig. 1). Differential effects of the two reinforcement schedules used in the present study may arise because in the RI schedule the probability of getting a reinforcer is increased by a pause in responding, while rapid responding is reinforced in the RR schedule (Fig. 3). Thus, the two schedules “push” responding in opposite directions. During the RR schedule rapid responding produces more reinforcers, thus the delay between responses and reinforcers decreases and the responding becomes more similar to that of children without ADHD. Thus, as we can see in figure 3: When the time intervals between responses and reinforcers get longer, the more the gradients differ. In accordance with this we expected a difference between the groups in the RI schedule but not in RR schedule.

4.3. Temporal response patterns

The temporal response dimension measured correlations between consecutive interresponse times (IRTs) during both the RI schedule and the RR schedule. A steeper and shorter delay gradient would according to the DDT imply that only responses with short interresponse times (IRTs) would be reinforced, and lead to the development of bursts of short IRTs. Because the RI and the RR schedule produces relatively stable response pattern, the behavior during RI and RR schedules is not expected to be temporally organized in any of the groups. Like we expected, we found no significant differences between the groups on this measure. This is as mentioned earlier in accordance with previous research (Aase & Sagvolden, 2005; Aase et al., 2006).

4.4. Alternative interpretations

There may be other interpretations of the behavioral variability we found in this study and commonly observed among children with ADHD. In order to test some of those we included some control measures.

4.4.1. Hyperactivity

An excess of motor activity has commonly been observed in children with ADHD (Taylor, 1998). Overactivity/hyperactivity can be observed as increased rate of various responses, which can be described as increased behavioral variability. Excessive motor activity, or hyperactivity, could possibly result in more variable responding in the ADHD group, especially in the ADHD-C group. A shorter and steepened delay gradient combined with failing extinction may according to the DDT lead to a high rate of responding with short IRTs (Sagvolden et al., 2005). In the present study hyperactivity was operationalized as number of responses during the task. There was no significant group difference in measures of number of responses during the two schedules (Fig. 12), thus the group differences in responding during the RI schedule cannot be accounted for by a general overactivity as measured in the present study. Total number of responses may, however, be a poor indicator for general overactivity.

4.4.2. Motor control

Poor motor control could possibly lead to more variable responding and lower predictability between consecutive responses. Clumsiness, poor motor control, longer and more variable reaction times, poor response timing, poor handwriting, and poor correlation of the activity of different body parts are predicted to be a result of a dysfunctional nigro-striatal dopamine branch, suggested to be impaired in children with ADHD (Sagvolden et al., 2005). In this study we measured motor control as the predictability of movements (moving the mouse) during the feeding situation. During the feeding situation coordinates of mouse cursor placement on the screen were recorded by 50 ms intervals. Predictability of movements was analyzed by autocorrelations between consecutive recordings (responses). The subjects in this study were instructed to use their nonpreferred hand during the test situation, something that would counter the effect of differential computer training among the children. According to the predictions from the DDT, the behavior of the ADHD group should be expressed in greater variability in mouse trajectory. This prediction was not supported by our results in that we found no significant differences in motor coordination between the three groups included in the analysis on these measures.

4.4.3. Barkley and deficient inhibition

In his theory of deficient behavioral inhibition Barkley (1997) predicts that children with ADHD will have more difficulties in building chains of behavior than others in the absence of immediate reinforcement, but not when frequent reinforcement is available. This is suggested to be caused by poor sustained attention resulting from poor inhibition. The finding from this study supports the predictions made by Barkley (Barkley, 1997), but he offers no underlying mechanism that can be empirically tested. The response unit that is supposed to be inhibited is difficult to define empirically (Catania, 1998). Thus the suggested mechanisms put forward by the DDT are a more specific explanation.

4.4.4. Sergeant and cognitive-energetics model

Two responses can by definition never be exactly the same, even if they belong to the same operant class. Belonging to the same operant class simply means that they produce the same consequences. This variability of responses is what makes selection possible, and is like mentioned earlier a prerequisite for learning. A shorter and steepened delay gradient as proposed by DDT lead to lack of stimulus control, which makes selection of responses deficient. Sergeant (2000) suggests that children with ADHD suffer from a nonoptimal energetic state. According to his model the energy necessary to complete a task, what he calls effort, is related to motivation. Reinforcement contingencies are presumed to have an influence on this allocation of energy to meet the demands of a task, and the model predicts that infrequent reinforcement will inadequately activate this effort pool, resulting in a lack of stimulus control and greater behavioral variability. This fits with the finding from studies showing differential effects of reinforcement contingencies (Aase & Sagvolden, 2005; Aase et al., 2006; Aase & Sagvolden, 2006), but in the same way as with Barkley (1997) this is a cognitive model which do not specify particular mechanisms that can be empirically tested.

4.4.5. A hypothesis on behavioral variability

In an attempt to explain response variability in children with ADHD, Russell and colleagues (2006) have presented a neuronal and glial energetic hypothesis. They propose that intra-individual variability observed during continual responding to externally-paced stimuli, as in Go/No go tasks, continuous performance tests (CPT) and stop-signal tasks; may arise from inefficient and inconsistent neuronal transmission of information. This is supposed to be caused by a deficient energy supply, specifically production of lactate, by the astrocytes (the major non-neuronal component of the central nervous system; and inadequately myelinated neurons slowing down the signal transmission. The authors suggest that deficient performance on the previous mentioned tasks may not be caused by a deficient inhibition as proposed by Barkley (1997) and others, but may rather be a failure of activation resulting in problems with response variability. Regarding specific aspects of the ADHD phenotype this hypothesis then proposes a physiological basis for the "*frequent, transient and impairing fluctuations in functioning, particularly during performance of speeded, effortful tasks*" (Russell et al., 2006). This hypothesis is primarily thought to account for the impaired performance efficacy on lengthy and effortful tasks. The task used in the present study may not demand the amount of effort suggested by the authors, thus making assumptions regarding the findings in this study would only be speculative.

4.5. Limitations and implications for future studies

It should be noted that our there were relatively few subjects in this sample of children. Thus, caution should be taken in making conclusions based on findings from the present study. In future studies a larger sample should be used and a comparison group of normal controls should be included. Ideally, this sample should also have had a group with ADHD-HI to investigate if this type of variable behavior only pertains to ADHD-C, or if ADHD-HI shows a similar behavioral pattern. The study should also be replicated in samples of older children in order to investigate how the proposed altered learning mechanisms may affect behavior during development. Ideally, there should have been a more even distribution of boys and girls in the sample. An additional limitation with this study is that only one task was used to measure behavioral variability.

Castellanos et al. (2005) has called for a more detailed analysis of intra-individual variability than what is attainable through the use of reaction times and standard deviations (SD). They argue that such measures do not capture the dynamic temporal fluctuations of behavior, and are therefore too crude to appropriately tap intra-individual variability. The use of autocorrelations in our study, and the studies done by Aase and colleges (Aase & Sagvolden, 2005; Aase et al., 2006) explores a new and promising method for studying the moment-to-moment dynamics of ADHD behavior.

5. Conclusion

The findings from the present study support predictions from the dynamic developmental theory of ADHD that a short and steepened delay-of-reinforcement gradient will result in more difficulties building chains of predictable behavior in children with ADHD compared to other children. The finding that this behavioral variability only was evident in the ADHD-C group and not in the ADHD-PI group, support the view that the problems associated with ADHD-PI may be quite different from the ones associated with ADHD-C, suggesting separate underlying mechanisms and etiologies (Barkley, 1997; Taylor, 1998; Johansen et al., 2002; Sagvolden et al., 2005). Thus, the assumption put forward by the DDT that altered learning mechanisms related to a shorter and steepened delay gradient may only pertain to ADHD-C, is supported. Since the DDT also predicts that ADHD-HI would excibit the same problems, a group with ADHD-HI should be included in future studies

The findings in this study may have implications in regard to behavioral interventions. Children in the ADHD-C group seem to have problems with building predictable chains of behavior, which is expected to be crucial for learning more complex behavior (Lashley, 1951). Behavioral interventions for these groups of children should accordingly be based on learning simple behavioral unit by establishing stimulus control, and then gradually increasing the complexity. Though important for the establishment of stimulus control (Sagvolden et al., 2005), simply ensuring immediate and frequent reinforcement seems to be insufficient with regard to establishing longer chains of behavior due to altered basic learning mechanisms in these children.

The use of autocorrelations of consecutive responses seems to be a promising approach for investigating the moment-to-moment dynamics in ADHD-related behavior.

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