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Mean response times, variability, and skew in the responding of ADHD children: a response time distributional approach

Craig Leth-Steensen [a,*], Zmira King Elbaz [b], Virginia I. Douglas [b]

[a] Department of Psychology, Northern Michigan University, 1401 Presque Isle, Marquette, MI 49855-5334, USA

[b] Department of Psychology, McGill University, 1205 Dr. Penfield Ave., Montreal, PQ, Canada H3A 1B1

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Abstract

Response time (RT) distributions from three fixed foreperiod conditions (2, 4, and 8 s) in a warned four-choice RT task were obtained for a group of boys with attention-deficit/hyperactivity disorder, combined type (ADHD; $n = 17$) and for two groups of normal control boys (age-matched, $n = 18$, and younger-aged, $n = 10$). Quantitative measures of distributional shape were derived by fitting the ex-Gaussian distributional model to the individual RT data. Statistical results indicate that the ADHD distributions differ from the age-matched control distributions with respect to the size of the tail (larger for the ADHD boys), but differ from the younger control distributions with respect to the location of the leading edge (slower for the younger control boys). Receiver operating characteristic (ROC) results reveal that the ex-Gaussian exponential component is highly diagnostic of the ADHD boys. © 2000 Elsevier Science B.V. All rights reserved.

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* Corresponding author. Tel.: +1-906-227-2935; fax: +1-906-227-2954.
E-mail address: clethste@nmu.edu (C. Leth-Steensen).

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1. Introduction

Cognitive psychologists have now studied the response performance of children with *attention-deficit/hyperactivity disorder* (ADHD) on a wide variety of information processing tasks (for a comprehensive review see Douglas, 1999). In conjunction with the fact that ADHD children often make more errors than control children, the most consistent finding in the ADHD cognitive literature is that the overall response times of ADHD children are typically both *slower* and *more variable* than those of control children. However, as noted by Douglas (1999), because much of the theoretical and empirical research involving ADHD children has focussed on more specific task manipulations, these two pervasive phenomena of slow and highly variable ADHD response times have still not been adequately addressed.

2. A response time distributional approach

This study will directly address these phenomena through a detailed statistical examination of the actual *distributions* of response times obtained from ADHD and control children within a four-choice warned reaction time (4C-WRT) task conducted at McGill University (King Elbaz, Douglas, Ditto & Van der Molen, 1999). In this task, groups of ADHD and age-matched control boys provided spatially compatible responses indicating which one of four, highly discriminable, stimuli had been presented in a stimulus display. On each choice trial, the relevant stimulus appeared at the conclusion of either a 2-, 4-, or 8-s fixed *foreperiod* (also known as a *preparatory interval* [PI]) that was marked by the presentation of an initial warning signal. In addition, parallel data were collected from a group of control boys several years younger than the ADHD and age-matched control boys to also determine whether the response time distributional profiles of the ADHD boys simply reflect an immature pattern of responding typical of younger children.

We were motivated to undertake an investigation of ADHD response time distributional data for several reasons. First, it is our view that dysfunctional *regulatory* or *control* processes are responsible for the performance problems associated with ADHD (see Douglas, 1999). In her recent review of the empirical ADHD findings, Douglas (1999) points out that the high degree of variability in ADHD performance on many cognitive tasks seems to signify a pervasive manifestation of regulatory problems involving the inconsistent allocation of effort. Hence, the acquisition of a better understanding of the nature of this variability represents an essential scientific step towards a determination of the precise role of this aspect of regulatory or control processing in ADHD.

Second, upon a closer examination of these types of data, we are continually struck by the fact that the response time distributions of ADHD children can typically be distinguished from those of control children more by the presence of a substantially larger number of abnormally slow responses than by an overall pattern of slow responses (see also Sergeant & Van der Meere, 1990, who reported experimental work in which suboptimal processing conditions mainly affected the right end of the response time distributions of hyperactive children). In other words, the standard *positive skewing*, or asymmetry, that is typically present in the response time distributions obtained within almost all psychological research paradigms (Luce, 1986) is highly exaggerated in the response time distributional profiles of ADHD children. Statistically, positive skew leads to a number of extreme values that have a disproportionate influence on the calculation of the response time mean and, similarly, on the size of the variance measure. We believe that this skew is an important empirical marker that reflects the presence of periodic attentional ‘lapses’ in the responding of ADHD children, in contrast to a general inability to respond quickly. Given the obvious nature of the potential theoretical implications of such a phenomenon, it is important to consider ways in which it might be measured in a *quantitative* fashion that then allows it to be subjected to a rigorous statistical analysis.

Third, there is a growing recognition that a quantitative study of the *shapes* of empirical response time distributions can provide much more information from a set of response time data than that which is given by the more standard statistical summary measures of the mean and the variance (Heathcote, Popiel & Mewhort, 1991; Hockley, 1984; Molenaar & Van der Molen, 1994; Ratcliff & Murdock, 1976). That is, response time distributional analyses can be used to describe psychological performance at a more fine-grained level than those standard measures and, thus, can also provide a fuller set of empirical constraints against which to evaluate any existing psychological theories for the underlying process(es) in question (e.g., Mewhort, Braun & Heathcote, 1992). Finally, the recent availability of a statistical package (RTSYS, Heathcote, 1996; see also Cousineau & Larochelle, 1997) now allows cognitive researchers to easily obtain quantitative summary measures of the shapes of response time distributions (in terms of the three parameters of the *ex-Gaussian* distributional model).

Our foray into response time distributional analyses has proven fruitful. In this article, it will be demonstrated that these analyses lead to the identification of one specific aspect of the ADHD distributional data that we believe uniquely characterizes the responding of ADHD populations in these types of cognitive psychological tasks; so much so, that this aspect will be shown to be highly diagnostic of ADHD in this sample of boys. Moreover, it will also be established that the two phenomena of slow and highly variable ADHD response times are intimately coupled, in that both can be explained mainly in terms of this same aspect of the ADHD response time distributions. Finally, the additional information obtained from these analyses will also show that, unlike either the response time means or standard deviations, the overall distributional pattern of ADHD responding can be dissociated from that of the younger control responding.

3. The ex-Gaussian distributional model

The ex-Gaussian distributional model can be used to provide useful quantitative measures of the distributional properties of a set of response times (Heathcote, 1996;

Luce, 1986; Ratcliff, 1979; Ratcliff & Murdock, 1976). This model assumes that each response time can be represented as the sum of a *normally distributed* random variable and an independent *exponentially distributed* random variable, and therefore, that the full distribution of response times can be characterized as a *convolution* of the normal and exponential distribution functions. Parametrically, the ex-Gaussian distribution has three constituents: mu (μ) and sigma (σ), that, respectively, describe the mean and standard deviation of the normal component, and tau (τ), that describes the mean of the exponential component. Fig. 1 shows the probability densities of two ex-Gaussian distributions, along with their normal and exponential distributional components. Each of the two ex-Gaussian distributions in Fig. 1 have identical normal components but differ with respect to their exponential components.

The theoretical focus on the ex-Gaussian distribution (e.g., Hohle, 1965, 1967) initially involved attempts to identify each of these two mathematical components with the time courses of various stages of processing, such as the encoding, decision, and motor stages (with not a lot of success; Luce, 1986; see also Heathcote et al., 1991; Hockley, 1984). However, in a more practical sense, whenever empirical response time distributions are fit with the ex-Gaussian model, the three ex-Gaussian parameters provide excellent quantitative measures which reflect the location of the *leading edge* of the distribution (μ and σ; i.e., the fastest response times) and the size of the *tail* (τ; i.e., the degree of positive

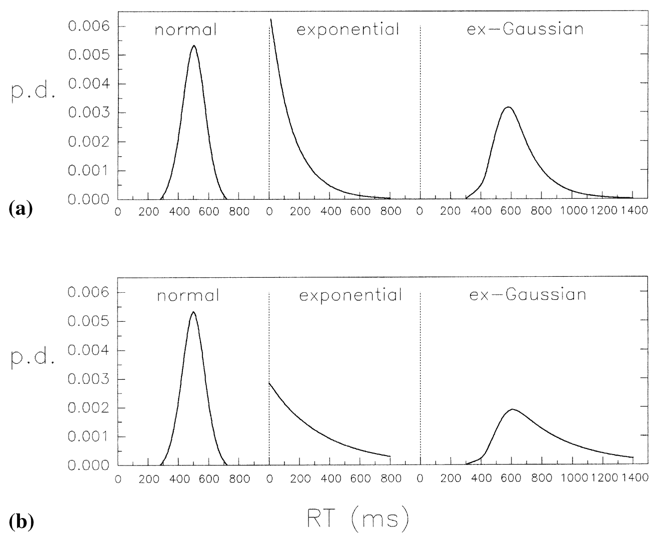

Fig. 1. Probability density (p.d.) functions for two normal distributions with $\mu = 500$ ms and $\sigma = 75$ ms ((a), (b)), two exponential distributions with $\tau = 150$ ms (a) and $\tau = 350$ ms (b), and the two resultant ex-Gaussian response time (RT) distributions.

skew).[1] Moreover, for present purposes, it is also important to note that the mean and variance of a distribution of response times (X) can each mathematically be related to the ex-Gaussian parameters in this fashion (Heathcote et al., 1991; Heathcote, 1996):

$$E(X) = \mu + \tau \tag{1}$$

and

$$\mathrm{Var}(X) = \sigma^2 + \tau^2. \tag{2}$$

4. Method

The data for the three experimental conditions of concern here were collected as part of a larger study conducted by King Elbaz et al. (1999). For details concerning the full set of experimental task manipulations used by those researchers see King Elbaz et al. (1999).

4.1. Subjects

Seventeen ADHD boys, 18 normal age-matched control boys, and 10 normal younger control boys participated in this study. The ages of the ADHD and the age-matched control boys ranged from 9 to 13 yr, with a mean age of 10 yr and 10 months for the ADHD boys and 11 yr and 1 month for the age-matched control boys. All of the younger control boys were 7 yr old, with a mean age of 7 yr and 4 months. Each boy was paid $10 for his participation.

The ADHD boys were recruited from the ongoing McGill University-Montreal Children's Hospital Hyperactivity Project. These boys had to meet the DSM-IV criteria for ADHD, combined type (American Psychiatric Association, 1994) as established in a structured parent interview (Diagnostic Interview Schedule for Children [DISC-R]; Shaffer, Schwab-Stone, Fisher & Cohen, 1993). The boys also received ratings beyond the established cut-off score from both parents and teachers on the hyperactivity index of the abbreviated conners rating scale (Goyette, Conners & Ulrich, 1978). The presence of attentional problems was further established using the IOWA version of the conners rating scale (Loney & Milich, 1982). Boys with known neurological damage; serious visual, auditory, or speech deficits; or IQ scores below 90 on the Wechsler intelligence scale for children (WISC-R) were excluded, as

[1] The concern here is with positive skew in a descriptive sense rather than its more mathematical interpretation (for a mathematical definition of skew and a derivation of its explicit relation to the three ex-Gaussian parameters see Heathcote, 1996). Actual empirical measures of skew using the *method of moments* can be quite unstable unless large numbers of sample observations are available (i.e., in the thousands; Ratcliff, 1979). Hence, the present characterization of skew in terms of the size of the tail of the distribution (i.e., τ) represents a more reasonable empirical way to quantify the degree to which it is present in the data.

were those whose problem behaviors were judged to be attributable to a stressful home environment.

The DISC-R interview (Shaffer et al., 1993) was also used to obtain information about comorbid symptoms of Oppositional and Conduct Disorder. In addition, the revised behavior problem checklist (RBPC; Quay & Peterson, 1983) was used to check for symptoms of anxiety and withdrawal. Because of the high prevalence of oppositional defiant disorder (ODD) in ADHD, boys who met DSM-IV criteria for ODD ($n = 11$) were not excluded from the ADHD sample; however, in all cases, the ADHD symptoms were considered to be more serious. Only one boy marginally met criteria for conduct disorder (CD). Although six boys scored above the criterion established by Quay and Peterson (1983) on the Anxiety-Withdrawal factor of the RBPC, interviews with parents and teachers established that anxiety symptoms were secondary to ADHD (i.e., the symptoms were considered to be less serious than the ADHD symptoms or developed later chronologically).

Boys who were receiving stimulant medication (methlphenidate in all cases) were taken off medication 24 h prior to testing. Because of the short half-life of methlphenidate, this procedure ensured that there would be minimal medication effects on task performance.

The normal control boys were recruited through newspaper advertisements. They were matched with the ADHD boys for IQ, socioeconomic status (SES), and age (for the age-matched control group). To rule out ADHD and other disorders, the DISC-R interview (Shaffer et al., 1993), the abbreviated Conners Parent Rating Scale (Goyette et al., 1978), the IOWA Conners Parent Rating Scale (Loney & Milich, 1982), and the Revised Behavior Problem Checklist (Quay & Peterson, 1983) were used.

4.2. Stimuli

The stimuli were four circles, 3 cm in diameter, arranged side by side (horizontally) in the centre of a computer screen. The circles were positioned on the far left, inner left, inner right, and far right of the screen, respectively.

4.3. Procedure

Each trial began with a warning signal that consisted of the appearance of four empty circles (which remained on the screen for the length of the foreperiod). At the end of the foreperiod, the circle designated as the target signal for that trial was filled (colored) in. For the experimental conditions that are relevant to this study, the boys were instructed to make a compatible choice response by pressing the response key that directly corresponded in position to the location of the target stimulus. These were four, clearly marked, keys on the centre row of the computer keyboard (in the positions of the letters S, F, J and L). Both the target circle and the three other (non-target) circles remained in view until the response was made. Following a response, the next trial was initiated after a fixed intertrial interval of 2500 ms.

Three of the experimental conditions from King Elbaz et al. (1999) were analysed in this study. These were the conditions involving the 2-, 4-, and 8-s foreperiods (or

PIs) that were presented in a *blocked* format. Eighty trial observations (20 for each of the four choice stimuli) were collected for each of the 2- and 4-s foreperiod conditions, and 72 trial observations (18 for each of the four choice stimuli) were collected for the 8-s foreperiod condition. The order of presentation of the three foreperiod conditions was randomly counterbalanced over boys.

Before beginning the task, all of the boys received instructions on the basic compatible response condition and performed a practice session of 16 trials. Speed and accuracy were emphasized equally. A boy had to respond correctly to five consecutive trials during the practice session before beginning the task. If this criterion was not met, he performed another practice session. The full testing session, including breaks, for all of the conditions in the King Elbaz et al. (1999) study lasted 2.5–3 h. Each boy received two short breaks of 10 min each and one long break of 25–30 min during which he was taken to the cafeteria for a snack.

The boys were tested individually in a room with a one-way mirror. The experimenter remained with them during the practice session. During the testing session, the experimenter left the room but closely observed the boys through the one-way mirror (they were always aware that they were being observed). For the purposes of the King Elbaz et al. (1999) study, heart-rate measures were also taken during testing to investigate the physiological changes taking place during the foreperiods. To obtain these measures, electrodes were placed on the chest and right ankle of each boy. These electrodes remained on the boys throughout the practice and testing sessions (except during the breaks).

5. Results

The dependent variables for the following statistical analyses were the mean response times, the standard deviations, and the estimates of the three ex-Gaussian parameters (μ, σ, and τ) for the set of trial observations obtained from each individual participant at each foreperiod condition. Only correct response times were used in the calculation of these measures, and the data for each condition were collapsed over the responses to each of the four possible choice stimuli. All of the following decisions concerning the statistical-testing and data-screening procedures were determined based on concerns raised and recommendations made in Stevens (1992), Tabachnick and Fidell (1989), and Keselman and Keselman (1990).

Ex-Gaussian distributional fits to the correct response times of each individual participant were obtained using the statistical package RTSYS Version 1.0 (Heathcote, 1996). To derive these fits, RTSYS employs an iterative search routine that provides *maximum likelihood estimators* for each of the ex-Gaussian parameters: μ, σ, and τ. Depending on the accuracy of the boy, whether or not he had any very extreme response times (an issue to be discussed shortly), and the foreperiod condition, the number of empirical observations used for each ex-Gaussian fit ranged from 62 to 80 observations (although for 1 ADHD boy only 48 correct observations were available at the 2-s foreperiod condition, and for 2 other ADHD boys only 55 and 58 correct observations, respectively, were available at the 8-s foreperiod condition). To assess the goodness-of-fit of the resultant ex-Gaussian fits to each of the corresponding empirical distributions, the data from each distribution were aggregated into a number of equal frequency bins (determined automatically by RTSYS), and a chi-square statistic was calculated by comparing the observed and expected number of response times within each bin.

5.1. Data screening

5.1.1. Outliers

There are two kinds of potential outliers that can be distinguished in the present set of data; one kind at the level of the trial responses of individual participants and one kind at the level of the participants themselves. With respect to outliers at the level of the trial responses, a conservative standard was adopted in this study of *censoring* any observations that were more than four standard deviations from a participant's mean response time for that foreperiod condition (in order to minimize the risk of removing any 'real' data, while still controling for very extreme observations). This criterion resulted in the removal for the following analyses of only 0.5%, 0.8%, and 0.2% of the observations from the data sets of the age-matched control, ADHD, and younger control boys, respectively.

With respect to outliers at the level of the participants, a *Mahalanobis* distance measure (D^2) was used to determine whether the set of response time means for any of the boys over all three of the foreperiod conditions differed significantly, at the $\alpha = 0.05$ level, from the *centroid* of the corresponding set of group means. This criterion resulted in the exclusion of three boys (one age-matched control boy and two ADHD boys), leaving 17, 15, and 10 boys in the age-matched control, ADHD, and younger control subsamples, respectively.

For this *reduced* sample, the mean observed values of each of the five dependent measures for each group and foreperiod condition (along with the mean percentage correct for completeness) are given in Table 1 and displayed in graphical form in Fig. 2. Similar age-matched control and ADHD data for the *full* sample (i.e., with no boys excluded) are given in Table 2. A comparison of the mean data in Tables 1 and 2 shows that the inclusion of the two outlying boys in the ADHD sample does have a substantial and potentially undue effect (especially at the 2- and 8-s foreperiods) on the observed values of both the group mean response times and the mean of the standard deviations. Note that the mean data in Tables 1 and 2 also indicate that the effect of excluding the one age-matched control boy is, in fact, fairly minimal.

5.1.2. Normality

The fact that human response time distributions are typically non-normal in form but are rather positively skewed (and, it will be shown, extremely skewed for two of the groups of boys in this study), along with the fact that some of the dependent variables under study here have been assumed a priori to be derived from non-normal random variables (e.g., τ), might imply that the required assumption of

Table 1
Mean dependent variable values and within-cell standard deviations (in parentheses) for the reduced sample

Group	Foreperiod (s)			Mean
	2	4	8	
Mean response time (ms)				
Control	626 (176)	647 (141)	705 (191)	659
ADHD	856 (146)	913 (188)	1030 (204)	933
Young control	961 (150)	1164 (167)	1199 (231)	1108
Mean standard deviation (ms)				
Control	157 (62)[a]	165 (58)	176 (85)	166
ADHD	329 (112)	379 (135)	423 (188)	377
Young control	264 (43)	389 (65)	374 (105)	342
Mu (ms)				
Control	500 (159)	512 (145)[a]	562 (171)[a]	525
ADHD	552 (91)	568 (105)	617 (89)	579
Young control	754 (120)	795 (131)	865 (199)	805
Sigma (ms)				
Control	81 (55)[a]	78 (43)[a]	75 (40)	78
ADHD	90 (42)	86 (44)	82 (36)	86
Young control	154 (64)	130 (75)[a]	175 (119)[a]	153
Tau (ms)				
Control	125 (72)[a]	135 (58)	142 (89)	134
ADHD	303 (111)	345 (129)	414 (186)	354
Young control	205 (70)	368 (92)	333 (104)	302
Percent correct				
Control	96.3	95.4	96.8	96.2
ADHD	93.0	95.1	94.5	94.2
Young control	94.0	95.8	94.5	94.8

[a] Significant Shapiro–Wilk test for violations of normality.

normality within the cells of the experimental design is likely violated for most of the dependent variables. Note, however, that with respect to univariate analyses of variance (ANOVAs), this assumption refers only to the normality of the measures actually being used in the ANOVAs and not to the normality status of the distributions of trial observations from which those measures are obtained.

For these data, consistent within-cell normality was indeed the norm for the reduced sample. Shapiro–Wilk tests (see Table 1) for violations of normality were significant, at the $\alpha = 0.05$ level, for only 8 of the 45 possible tests (3 groups $\times$ 3 foreperiods $\times$ 5 dependent variables). Furthermore, six of these significant violations occurred for data that were obtained from the group of age-matched control boys, and four of them involved measures of σ. However, as Table 2 indicates, the addition of the two ADHD boys to the full sample resulted in eight violations of normality for the 15 possible tests involving the ADHD boys.

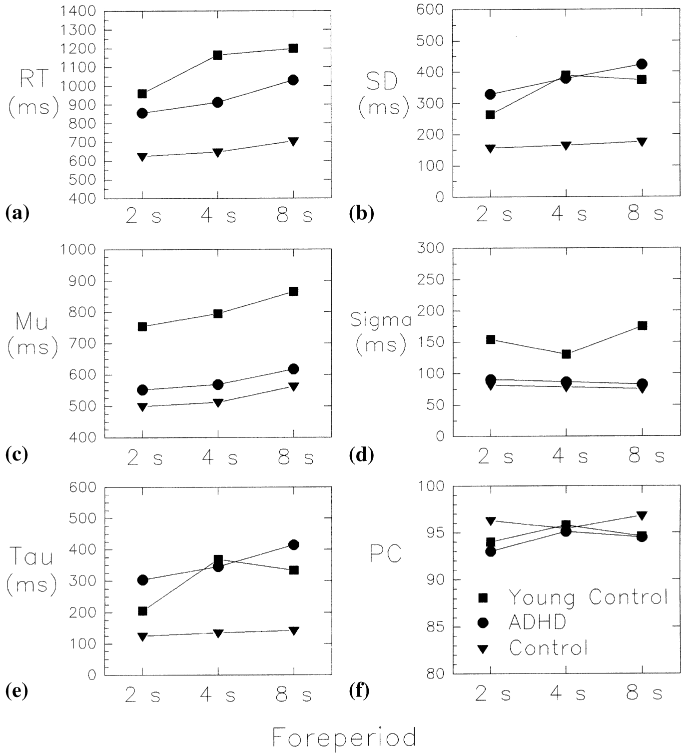

Fig. 2. Average values (for correct responses only) at each foreperiod condition of the response time means (RT; (a)), the standard deviations (SD; (b)), μ (Mu; (c)), σ (Sigma; (d)), τ (Tau; (e)), and percentage correct (PC; (f)) measures for the younger control (filled squares), the ADHD (filled circles), and the age-matched control (filled inverted triangles) reduced-sample groups.

5.1.3. Multisample sphericity

The validity of univariate tests of significance for split-plot designs also requires both that the *sphericity* condition be met and that the variance–covariance matrices be *homogeneous* over the participant groups. As before, note that the homogeneity assumption applies only to the set of values actually being used in the ANOVAs (i.e., the statistical summary measures obtained for each participant in each group at each foreperiod condition) and not to any group differences in the variances of the distributions of trial observations.

The degree to which the sphericity condition is violated can be determined by the value of ϵ (the Greenhouse–Geisser epsilon d.f. adjustment factor); smaller values of ϵ indicate more substantial violations of sphericity. For these data, the values of ϵ for the reduced sample were 0.985, 0.960, 0.969, 0.971, and 0.981 for the means, the standard deviations, and the estimates of μ, σ, and τ, respectively. For the full sample, these same values of ϵ were 0.888, 0.846, 0.834, 0.756, and 0.922, respectively. The presence of *heterogeneity* of the variance–covariance matrices is marked by significant Box tests. For the reduced sample, four of the five Box tests were

Table 2
Mean dependent variable values and within-cell standard deviations (in parentheses) for the full-sample ADHD and age-matched control

Group	Foreperiod (s)			Mean
	2	4	8	
Mean response time (ms)				
Control	617 (176)	667 (160)	705 (185)	663
ADHD	956 (331)[a]	920 (205)	1101 (274)[a]	992
Mean standard deviation (ms)				
Control	154 (63)[a]	171 (62)	178 (83)	168
ADHD	412 (261)[a]	398 (180)	509 (301)[a]	440
Mu (ms)				
Control	495 (157)	535 (172)	559 (167)[a]	530
ADHD	582 (144)[a]	556 (106)	619 (83)	586
Sigma (ms)				
Control	81 (54)[a]	89 (61)[a]	75 (36)	82
ADHD	129 (152)[a]	88 (41)	94 (54)[a]	104
Tau (ms)				
Control	122 (72)[a]	132 (58)	146 (88)	133
ADHD	374 (228)[a]	364 (180)	482 (259)	407
Percent correct				
Control	96.3	95.4	96.6	96.1
ADHD	93.0	95.2	94.2	94.1

[a] Significant Shapiro–Wilk test for violations of normality.

significant at the $\alpha = 0.05$ level (the tests for the standard deviations and the estimates of μ, σ, and τ). For the full sample, Box tests were significant for all five of the dependent variables. [2]

5.1.4. Ex-Gaussian fits

The chi-square tests of the fits of the ex-Gaussian distributional model to the individual data at each foreperiod condition indicated that only 4, 5, and 8 of these fits (out of a possible 54, 51, and 30 fits) were associated with significant chi-square values, at the $\alpha = 0.05$ level, for the age-matched control, ADHD, and younger control boys, respectively. Although a significant chi-square value indicates that the ex-Gaussian model does not adequately characterize that particular set of distributional data, it is reasonable to assume that these fits still provide important and

[2] Fortunately, split-plot univariate ANOVAs are actually quite robust against violations of the homogeneity assumption if the covariances matrices at each of the levels of the between-subjects factor do not differ by an extreme amount (e.g., by more than a factor of 3 or so). Hence, the following univariate statistical analyses of these dependent measures should not unduly be affected by these violations.

meaningful quantitative information, perhaps the best that is available, regarding the shapes of those distributions. Hence, the resultant ex-Gaussian parameters for each of these cases were still used as observations in the following analyses.

5.2. Inferential testing

Five univariate ANOVAs were performed; one for each of the five dependent variables. Each ANOVA involved a 3 (group) $\times$ 3 (foreperiod) split-plot factorial design with repeated measures over the levels of the second factor. Also the results of inferential tests for two sets of separate planned of major interest were, but non-orthogonal, *contrasts*. One of these sets of contrasts involved comparisons of the levels of each of the dependent variables for the ADHD group against the age-matched control group. The second set of contrasts involved comparisons of the levels of each of the dependent variables for the younger control group against the ADHD group.

The results of all inferential tests are reported for the reduced sample. For the full sample, statistical results are reported only for those occasions in which they differed substantially from the corresponding reduced sample results (in fact, the statistical inferences drawn from practically all of the test results of both samples were identical). Although the conventional degrees of freedom are provided for all of the statistical results reported here, all of the corresponding inferential tests involving the repeated measures factor were based on significance levels determined by the Greenhouse–Geisser epsilon adjusted degrees of freedom. Due to the presence of unequal sample sizes over the groups of boys, the inferential tests for each of the main effects and the interaction within each ANOVA were performed using the unique contributions of those effects to the overall partitioning of the total sum of squares.

Given the number of separate ANOVAs performed here, a *Bonferroni* criterion was used to protect against Type I inferential errors. [3] Because the values of both the means and the standard deviations are directly determined by the values of the three ex-Gaussian parameters (i.e., see Eqs. (1) and (2)), it was assumed that only three independent ANOVAs were being performed. Hence, the critical familywise α level used for all of the inferential tests for the main effects and the interactions was $\alpha_{FW} = 0.05/3 = 0.0167$. Because the number of contrasts being examined within

[3] Bonferroni adjustments to critical alpha levels have not been used until now because in most of the previous statistical testing (i.e., the sets of Shapiro–Wilk tests, Box tests, and chi-square tests for the goodness of the ex-Gaussian fits) the concern has been with whether the tests *do not* show significance (which then implies that normality, homogeneity, and the ex-Gaussian model hold, respectively). Hence, for these cases, reducing critical alpha levels actually increases the 'liberalism' of the tests (with respect to our purposes; i.e., by increasing the risk of a false negative). Regarding the set of tests that used significantly large Mahalanobis distance measures as a means to exclude outlying participants from the full sample, we think that the differences between the ADHD data given in Tables 1 and 2 more than justifies our use of this exclusion criterion. Furthermore, the relevant data and inferential test results for both samples is always reported throughout.

each ANOVA design was two, the critical per comparison α level used for all of those tests was $\alpha_{PC} = 0.05/(3 \times 2) = 0.0083$. [4]

5.2.1. Mean response times

For both the reduced and the full samples, the main effects of group ($F = 26.56$; d.f.1 = 2; d.f.2 = 39; $P < 0.001$) and foreperiod ($F = 29.94$; d.f.1 = 2; d.f.2 = 78; $P < 0.001$) were significant. The Group × Foreperiod interaction ($F = 4.07$; d.f.1 = 4; d.f.2 = 78; $P < 0.0167$) was significant for the reduced sample but fell slightly short of significance for the full sample ($F = 3.25$; d.f.1 = 4; d.f.2 = 84; $P > 0.0167$). The planned contrast analyses for both samples revealed that the mean response times of the ADHD group differed significantly from those of the age-matched control group ($F = 22.94$; d.f.1 = 1; d.f.2 = 39; $P < 0.001$) but that the mean response times of the younger control group did not differ significantly from those of the ADHD group ($F = 7.12$; d.f.1 = 1; d.f.2 = 39; $P > 0.0083$).

5.2.2. Standard deviations

For both the reduced and the full samples, the main effects of group ($F = 28.28$; d.f.1 = 2; d.f.2 = 39; $P < 0.001$) and foreperiod ($F = 9.97$; d.f.1 = 2; d.f.2 = 78; $P < 0.001$) were significant. The Group × Foreperiod interaction ($F = 2.35$; d.f.1 = 4; d.f.2 = 78; $P > 0.05$) was not significant for either sample. The planned contrast analyses for both samples revealed that the standard deviations of the ADHD group differed significantly from those of the age-matched control group ($F = 50.10$; d.f.1 = 1; d.f.2 = 39; $P < 0.001$) but that the standard deviations of the younger control group did not differ significantly from those of the ADHD group ($F = 1.01$; d.f.1 = 1; d.f.2 = 39; $P > 0.05$).

5.2.3. Mu

For both the reduced and the full samples, the main effects of group ($F = 15.39$; d.f.1 = 2; d.f.2 = 39; $P < 0.001$) and foreperiod ($F = 18.70$; d.f.1 = 2; d.f.2 = 78; $P < 0.001$) were significant. The Group × Foreperiod interaction ($F = 0.61$; d.f.1 = 4; d.f.2 = 78; $P > 0.05$) was not significant for either sample. The planned contrast analyses for both samples revealed that the values of μ for the ADHD group did not differ significantly from those of the age-matched control group ($F = 1.41$; d.f.1 = 1; d.f.2 = 39; $P > 0.05$) but that the values of μ for the younger control group did differ significantly from those of the ADHD group ($F = 18.20$; d.f.1 = 1; d.f.2 = 39; $P < 0.001$).

[4] Related to this issue is the fact that, given the number of dependent variables used, it would also have been possible to perform a less conservative *multivariate analysis of variance* (MANOVA) on these data, especially with respect to the three ex-Gaussian parameters. However, the interest here is not in determining whether there is a significant overall difference between the values of these three parameters together (in some sense, any significant differences in the means and the standard deviations already provides this information) but, rather, in determining which of the three ex-Gaussian parameters lead to that difference (for which a series of univariate tests is more appropriate).

5.2.4. Sigma

For both the reduced and the full samples, only the main effect of group ($F = 9.21$; d.f.1 = 2; d.f.2 = 39; $P < 0.0167$) was significant. Neither the main effect of foreperiod ($F = 1.00$; d.f.1 = 2; d.f.2 = 78; $P > 0.05$) nor the Group × Foreperiod interaction ($F = 1.21$; d.f.1 = 4; d.f.2 = 78; $P > 0.05$) was significant for either sample. The planned contrast analyses for both samples revealed that the values of σ for the ADHD group did not differ significantly from those of the age-matched control group ($F = 0.21$; d.f.1 = 1; d.f.2 = 39; $P > 0.05$). However, the values of σ for the younger control group did differ significantly from those of the ADHD group ($F = 12.76$; d.f.1 = 1; d.f.2 = 39; $P < 0.0083$) for the reduced sample but not for the full sample ($F = 5.03$; d.f.1 = 1; d.f.2 = 42; $P > 0.025$).

5.2.5. Tau

For both the reduced and the full samples, the main effects of group ($F = 29.19$; d.f.1 = 2; d.f.2 = 39; $P < 0.001$) and foreperiod ($F = 11.96$; d.f.1 = 2; d.f.2 = 78; $P < 0.001$) were significant, as was also the Group × Foreperiod interaction ($F = 3.92$; d.f.1 = 4; d.f.2 = 78; $P < 0.0167$). The planned contrast analyses for both samples revealed that the values of τ for the ADHD group differed significantly from those of the age-matched control group ($F = 53.82$; d.f.1 = 1; d.f.2 = 39; $P < 0.001$) but that the values of τ for the younger control group did not differ significantly from those of the ADHD group ($F = 2.22$; d.f.1 = 1; d.f.2 = 39; $P > 0.05$).

5.2.6. Summary

The results of the inferential tests for the two contrasts comparing the levels of each of the five dependent variables over the participant groups are summarized in Table 3. For both the mean response times and the standard deviations, these results indicate that the ADHD group differed (i.e., slower and more variable) from the age-matched control group, but not from the younger control group. With respect to the three ex-Gaussian parameters, these results indicate that the ADHD group differed from the age-matched control group only on measures of τ (i.e., larger for the

Table 3
Results of the inferential tests for the planned contrasts

	Contrast	
Dependent Measure	Age-matched control group vs. ADHD group	ADHD group vs. younger control group
Mean RT	Significant	Not significant
SD	Significant	Not significant
Mu	Not significant	Significant
Sigma	Not significant	Significant
Tau	Significant	Not significant

ADHD group), but differed from the younger control group on measures of both μ and σ (both larger for the younger control group).

In addition to the group effects, significant foreperiod effects (i.e., increases in values of the dependent measures over increases in the length of the foreperiod) were present for all of the dependent variables except σ. However, foreperiod (or PI) effects will not be addressed within this article. For a full discussion of the mean response time foreperiod results for the ADHD and the age-matched control groups see King Elbaz et al. (1999). As well, for an excellent theoretical discussion of foreperiod effects see Niemi and Naatanen (1981), for some previous empirical ex-Gaussian response time results involving a foreperiod task see Hohle (1965, 1967), and for some recent findings comparing the response time performances of schizophrenic and control groups on both manual and saccadic foreperiod tasks see Zahn, Roberts, Cohen, and Schooler (1998). Significant Group $\times$ Foreperiod interactions were present only for the mean response times and for the measures of τ. These overall interaction effects were evidently due to the substantial differences in foreperiod profiles across the groups that are apparent in Fig. 2 for those two dependent variables.

5.3. Vincentized group response time distributions

For each group at each foreperiod condition, group response time distributions were derived using the *Vincent averaging* technique recommended by Ratcliff (1979; see also Heathcote, 1996). These group response time distributions are displayed in Fig. 3 as Vincent histograms. Within such histograms, distributions of observations are represented as a series of rectangles of equal area. The solid curves in Fig. 3 represent the ex-Gaussian fits to each of those distributions (none of the corresponding chi-square goodness-of-fit tests were significant). All of the group differences in distributional location and shape that could be inferred from the previously reported group differences in the estimated values of the three ex-Gaussian parameters are clearly illustrated in these plots.

5.4. Receiver operating characteristic analysis

Finally, the *diagnostic accuracy* of each of the five dependent variable measures was examined by applying *receiver operating characteristic* (ROC) methodology (Hanley, 1989; Hanley & McNeil, 1982; Swets, 1988) to the individual data of the ADHD and the age-matched control groups (for another recent application of this methodology to an ADHD sample see Chen, Faraone, Biederman & Tsuang, 1994). Diagnostic accuracy refers to the degree to which a 'test' measure (i.e., each of the five dependent variables) can be used to correctly discriminate between membership in a group of interest (in this case, the full sample ADHD group) and membership in a comparable control group (in this case, the full sample age-matched control group).

ROC analyses of numerical test measures involves choosing a number of *cut points* (called 'decision criteria' in *signal detection theory*) along the continuum of

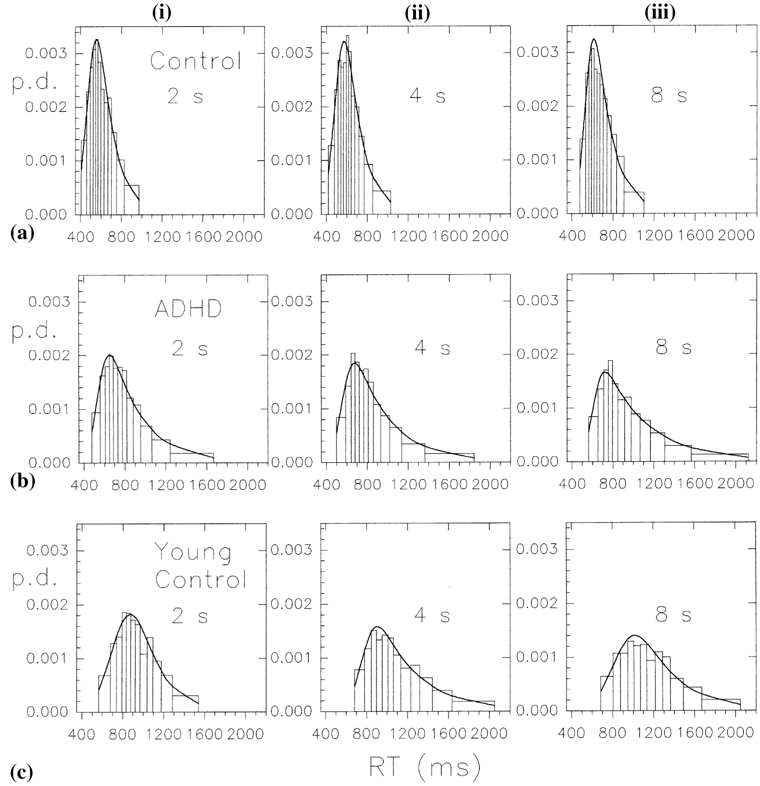

Fig. 3. Probability density (p.d.) histograms for the distributions of correct response times (RT) Vincent averaged over the participants in each of the age-matched control (a), ADHD (b), and younger control (c) reduced-sample groups at each of the 2-s (i), 4-s (ii), and 8-s (iii) foreperiod conditions. For each of the probability density histograms, the fitted ex-Gaussian distribution functions (solid lines) are also shown.

possible values of the test measure and determining, for each cut point, the proportion of cases correctly classified as ADHD (the *true-positive* fraction [*TP*]; also referred to as the *hit* rate or *sensitivity*) and the proportion of cases incorrectly classified as ADHD (the *false-positive* fraction [*FP*]; also referred to as *false-alarm* rate or 1 − *specificity*). ROC curves are plots of the TP fraction (on the ordinate) against the FP fraction (on the abscissa). As with the psychophysical discrimination of ‘signals’ from ‘noise’, the closer an ROC curve is to the top-left corner of this plot, the greater is the discriminative performance of the corresponding test measure. High discriminative performance indicates that the distributions of the individual test measure values for each of the two groups in question are highly non-overlapping. ROC curves that fall very close to the main diagonal of this plot indicate that the corresponding test measure provides only chance-level discrimination and, hence, is highly non-informative.

The ROC analysis was performed here by first averaging each of the five dependent variables across the three foreperiod conditions for each of the boys in the

Table 4
Cut points used in the ROC analyses along with the estimated areas (A) under the ROC curve for each dependent measure

Measure	Cut points (ms)						A	SE(A)
	1	2	3	4	5	6		
Mean RT	650	720	790	860	930	1000	0.904	0.049
SD	150	185	220	255	290	325	0.961	0.031
Mu	450	520	590	660	730	800	0.621	0.103
Sigma	35	70	105	140	175	210	0.619	0.097
Tau	100	135	170	205	240	275	0.961	0.036

full sample ADHD and age-matched control groups. These individual marginal means were then sorted from smallest to largest. For each dependent measure, six different equispaced cut point values were chosen (see Table 4), and TP and FP fractions were calculated by determining the proportion of boys in each of the respective ADHD and age-matched control groups with dependent variable values above the value of each cut point. The resultant ROC curves are given in Fig. 4.

Non-parametric estimates of the *area* (A) beneath each of the ROC curves in Fig. 4 (calculated according to the method suggested by Hanley & McNeil, 1982, by using the six cut points to derive seven 'rating' categories) are also given in Table 4 along with their corresponding estimated standard errors. [5] These areas provide an index of the diagnostic accuracy of each of the five dependent measures (Hanley & McNeil, 1982). The values of A in Table 4 indicate that: (a) both the measures of τ and the standard deviations are highly (and equivalently) diagnostic of ADHD, (b) the mean response times are also quite diagnostic of ADHD (with an accuracy that is smaller than that of both τ and the standard deviations but cannot, however, be statistically differentiated from the accuracy of those measures according to the test prescribed by Hanley & McNeil, 1983), and (c) the measures of both μ and σ have very low diagnostic value.

6. General discussion

The results of the statistical and ROC analyses of the ex-Gaussian distributional measures performed here are very clear: The ADHD responding can be differentiated from the age-matched control responding almost exclusively in terms of the size of

[5] Parametric estimates of A typically make use of assumption that the test measures are normally distributed within each of the two groups to derive estimates of A_z (i.e., the binormal model; Hanley, 1989). When sample sizes are large enough, parametric estimates of A are generally preferable to non-parametric ones because the latter tend to slightly underestimate the true A and overestimate its standard error. However, given the number of participants studied here, non-parametric estimates should be acceptable for present purposes.

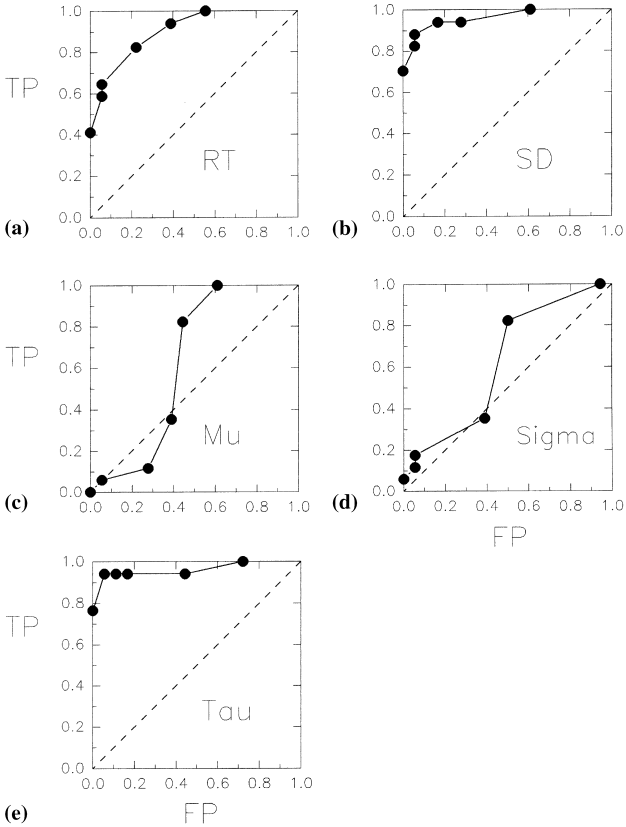

Fig. 4. ROC curves plotting the full-sample true-positive (TP) fractions against the full-sample false-positive (FP) fractions for each cut point value (the filled circles; cut point values increase from the top right to the bottom left of each plot for the response time means (RT; (a)), the standard deviations (SD; (b)), μ (Mu; (c)), σ (Sigma; (d)), and τ (Tau; (e)).

the tails of their respective response time distributions (i.e., in the value of τ). In essence, the faster correct responses of the ADHD boys are almost as fast as those of the age-matched control boys, whereas the slower ADHD responses are much slower. This result suggests that the consistent finding of larger mean responses times for ADHD children in comparison to age-matched control children is not due to a major generalized slowing down of all ADHD responses (which would also affect the values of μ), but arises because ADHD response sets contain a greater proportion of abnormally slower responses. Although this fact is somewhat obvious from a visual comparative inspection of the ADHD and age-matched control response time distributions, the major contribution of this research has been to obtain quantitative measures of the shapes of these distributions so that this fact can be verified statistically.

Furthermore, given the inherent mathematical relations between the three ex-Gaussian parameters and the standard measures of the mean and the variance (i.e., Eqs. (1) and (2)), it is apparent that it is mainly this aspect (τ) of the responding of these ADHD boys that leads to *both* their slower observed response time means and their larger observed variabilities (i.e., because they do not differ significantly from the age-matched control boys on the remaining two ex-Gaussian parameters: μ and σ). Hence, this finding establishes that these two empirical phenomena do not, in fact, represent two separate aspects of the overall performance deficits observed in ADHD responding but are both seemingly a consequence of an extreme exaggeration in the sizes of the tails of the ADHD response time distributions. Moreover, it should also be apparent that in the results of the ROC analyses the high diagnostic accuracies for both the response time means and standard deviations are due solely to τ.

Finally, it is also evident that the distributional data of the younger control boys are *qualitatively* different from the distributional data of the ADHD boys. Although the response time distributions of these two groups of boys are both highly positively skewed (i.e., are characterized by large values of τ), these distributional data also indicate that the responding of the younger control boys, unlike the ADHD responding, is further marked by both an overall slowing and spreading out of the entire ensemble of response times (i.e., the distributions of the younger control boys are also characterized by large values of μ and σ). [6]

These results, however, leave one other potentially important issue unresolved; namely, whether or not there is *any* difference between the responding of the ADHD and the age-matched control boys with respect to the value of μ. As mentioned, the ROC results indicate that measures of μ are highly non-diagnostic (in fact, for two of the larger cut points the FP fraction actually exceeds the TP fraction). Moreover, within the statistical analysis, the relevant difference contrast for this parameter did not reach statistical significance. Nonetheless, the consistency of the overall direction of the differences at each of the foreperiods suggests that the average value of μ does, in fact, differ slightly between these two groups. However, the size of this effect is quite small relative to the effect for τ and would require a substantial amount of statistical power to verify.

It is also important to reiterate that we are not making the claim here that these response time data were generated from some underlying ex-Gaussian cognitive process. In fact, there are many other possible ways through which this kind of distributional data could be mathematically characterized (e.g., the *lognormal* distribution; for some other distributional possibilities see Ratcliff, 1993; Ulrich & Miller, 1994; Van Zandt, in press). The ex-Gaussian distributional model has been used here simply because it represents a useful way to mathematically separate out

[6] Note, as well, that our full set of results indicates that the responding of the younger control boys differs from the responding of the older control boys with respect to all three of the ex-Gaussian parameters. This is a phenomenon which we believe could also be very important with regard to furthering an understanding of the developmental differences that are often observed in response time measures obtained from children of different ages (in fact, the use of the ex-Gaussian for this purpose was originally suggested by Hohle, 1967).

the components of the shapes of the observed response time distributions into a set of summary parameters that have some intuitive descriptive meaningfulness.

6.1. The tau effect

Although for the present these results can only be generalized to the sample of boys and the fixed foreperiod task conditions studied by King Elbaz et al. (1999), we strongly believe that these findings indicate that one of the keys to understanding the behavioral phenomena exhibited by ADHD children in cognitive experimental tasks lies in determining the underlying cognitive variables that lead to this large effect in τ. In light of these findings, it is certainly evident that explicit distributional analyses of ADHD data within other experimental paradigms are necessary in the near future in order to further clarify the full extent of this effect.

In essence, this *tau effect* represents an important new challenge for all existing theories of these phenomena. With respect to dysfunctional regulatory or control processes, Douglas (1999) has proposed that a major processing problem in ADHD involves a failure to allocate adequate attention or effort to meet task demands. Such a failure could arise in ADHD due to a deficient allocation of *energetic resources* (i.e., the effortful maintenance of optimal arousal and activation levels) within an information processing model such as Sanders' (1983) *cognitive-energetical* performance model. With respect to the 4C-WRT task, it could be assumed that these energetical resources are needed in order to maintain a *consistent* state of preparation for the processing of the stimulus information and for the generation of the accompanying response.

Although much additional theoretical work is needed in order to make the relation between energetical resource allocation and response time more explicit (for an excellent general report on the current state of theorizing regarding the integration of energetical constructs within information processing models of cognition see Van der Molen, 1996), we believe that the tau effects observed here are consistent with the assumption of an underlying defective effort control mechanism in ADHD children. For example, difficulties involving the allocation of effort could lead to the occurrence of a number of attentional lapses during the course of information processing. Experimental trials characterized by many such lapses would then increase the number of observed responses on the slow end of the response time distribution. Moreover, the fact that the ADHD and control distributions do not substantially differ here with respect to the fast end of their respective response time distributions (i.e., in the locations of the leading edge), suggests that ADHD children are often capable of executing the task requirements as efficiently as age-matched control children, but that they just cannot do so as regularly. This account also agrees with Sanders' (1983) previous argument that in contrast to *computational* factors which should directly effect the processing times of all responses (and, hence, shift the locations of the response time distributions), the effects of energetical factors "may strongly vary between individual trials... [and hence] their effect is usually most pronounced at the higher end of the [response time] distribution and may indeed be absent at the lower end" (p. 83; e.g., see Smulders, Kenemans, Jonkman & Kok's, 1997, recent findings regarding the effect of sleep loss on response time distribution functions).

Finally, because measures of τ are quite comparable for both the ADHD boys and the younger control boys, it is necessary to consider the possibility that both groups of boys might be susceptible to attentional lapses in information processing. If so, then the tau effect in the responding of the ADHD boys could, perhaps, signal the presence of developmental delay within the ADHD group. On the other hand, the marked differences between the younger control boys and the ADHD boys with respect to measures of both μ and σ, indicate that the responding of the younger control boys is also both considerably slower and more erratic than the responding of the ADHD boys. Thus, these differences in μ and σ between the younger control and the ADHD groups also signal the presence of additional information processing problems of a more generalized nature within the group of younger controls.

6.2. Tau's potential as a diagnostic tool

Given the task of classifying individuals as having ADHD or not having ADHD, it is of obvious benefit to have *objective* measures that can be used to assist in the diagnostic process. The ROC results in this article suggest that the level of response time distributional skew, as measured by the ex-Gaussian τ parameter, has this potential. Hence, it will be important, first, to conduct further research that will help to delimit the conditions (e.g., the optimal types of cognitive tasks, the optimal number of trial observations, etc.) under which measures of τ can best be used to classify individuals with ADHD and, second, to conduct similar ROC analyses involving τ with much larger samples of individuals in order to determine the true diagnostic value of this measure.

6.3. Additional statistical issue

In addition to demonstrating the tau effect in the responding of ADHD children, this article has addressed one other important underlying statistical issue. This issue pertains to the statistical analysis of response time data obtained from ADHD populations. Given that the observed distributions of trial observations for the ADHD children are both decidedly non-normal (i.e., highly positively skewed) and much more variable than the age-matched control distributions, what implications do these aspects have with respect to the proper statistical treatment of these data? For example, empirical researchers are generally trained to recognize such situations and to automatically make corrections through the application of statistical procedures such as normalizing transformations. Furthermore, it is quite standard for cognitive researchers to use various data-trimming approaches in order to omit empirical trial observations that seem somewhat removed from the rest of the response data (i.e., 'outliers'; for a recent discussion of these approaches and some issues related to them see Ratcliff, 1993; Ulrich & Miller, 1994). However, this research demonstrates that such remedial measures are not only *unnecessary* (see the previous section on data screening) but are also quite *inappropriate* for these kinds of data. Because almost all of the effect that differentiates the response time performances of the ADHD and the age-matched control groups in this study is present in the tails of the response time distributions, the use of normalizing transformations is tantamount to the *artificial elimination of that effect*. The analysis of medians instead of means, as well as the use of excessive data trimming is problematic for the same reason. To conclude, we believe that the tau effect in the response time distributions of ADHD children is an effect that needs to be studied and not removed from the data.

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