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CO-REGULATION OF MOVEMENT SPEED AND ACCURACY BY CHILDREN WITH HEAVY PRENATAL ALCOHOL EXPOSURE^{1, 2}

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Summary

The study investigated how children with heavy prenatal alcohol exposure regulate movement speed and accuracy during goal-directed movements. 16 children ages 7 to 17 years with confirmed histories of heavy *in utero* alcohol exposure, and 21 nonalcohol-exposed control children completed a series of reciprocal tapping movements between two spatial targets. 5 different targets sets were presented, representing a range of task difficulty between 2 and 6 bits of information. Estimates of percent error rate, movement time, slope, and linear fit of the resulting curve confirmed that for goal-directed, reciprocal tapping responses, performance of the group with prenatal alcohol exposure was described by a linear function, as predicted by Fitts' law, by sacrificing movement accuracy. The index of performance was the same for the two groups: it initially increased, then leveled off for more difficult movements.

Fetal alcohol spectrum disorder is an umbrella term for a continuum of neurobehavioral problems associated with maternal consumption of alcohol during pregnancy. At the extreme end of the continuum are children with fetal alcohol syndrome, which is diagnosed on the basis of central nervous system dysfunction, pre- and/or postnatal growth retardation, and a distinct pattern of craniofacial anomalies (Jones & Smith, 1973). Estimates place the overall incidence of fetal alcohol syndrome between 2.8 to 4.6 cases per 1,000 live births in the USA and Western Europe (Sampson, Streissguth, Bookstein, Little, Clarren, Dehaene, *et al.*, 1997), although incidence rates can be as high as 65.2 to 74.2 per 1,000 children in other geo-graphical areas (Viljoen, Gossage, Brooke, Adnams, Jones, Robinson, *et al.*, 2005). Incidence rates increase considerably when including children who have histories of heavy prenatal alcohol exposure but who do not have the three defining characteristics of fetal alcohol syndrome. For assessment purposes, both groups of children are considered a homogeneous group, since neuroimaging investigations and neurobehavioral testing indicate that dysmorphic and nondysmorphic children with prenatal alcohol exposure experience similar structural anomalies in the central nervous system and manifest many of the same intellectual, cognitive, and motor deficits (Mattson, Riley, Gramling, Delis, & Jones, 1997).

With regard to motor skills of children with prenatal alcohol exposure, previous researchers have reported developmental delays of early motor milestones (Autti-Ramo & Granstrom, 1991), deficits in balance coupled with slowed transcortical loop processing time (Roebuck, Simmons, Mattson, & Riley, 1998), slower choice reaction time (Simmons, Wass, Thomas, & Riley, 2002), less accurate and more variable responses during tasks requiring anticipation timing and velocity timing accuracy (Wass, Simmons, Thomas, & Riley, 2002), and dysfunctional central clock and peripheral timing (Simmons, Levy, Riley, Madra, &

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Mattson, 2009). However, much remains unknown about motor control processes in this clinical group, particularly when combinations of parameters such as movement speed and accuracy must be co-regulated.

The tradeoff between movement speed and accuracy has been metrically expressed by Fitts' law (Fitts, 1954) as

$$MT=a+b\log_2 2D/W$$

where, MT is the average movement time, a and b are the intercept and slope of the linear function, respectively, D is the distance to the target, and W is the width of the target. The difficulty of the movement (known as the index of difficulty and measured in bits of information) is defined as the logarithmic expression of 2D/W. Altering the width and distance variables changes this index. According to the law, movement time increases linearly with increasing task difficulty, with the slope of the function reflecting the sensitivity of the sensorimotor system to increasing index of difficulty. When the difficulty index is divided by movement time (known as the index of performance and measured in bits per second), the amount of information that is processed per unit of time is estimated.

For reciprocal tapping tasks, Fitts' law describes the speed-accuracy relation for typically developing individuals (Mottet, Guiard, Ferrand, & Bootsma, 2001; Lambert & Bard, 2005) and some clinical syndromes including cerebral palsy (LeGare, Wolak, & Doyle, 1994), schizophrenia (Carnahan, Aguilar, Malla, & Norman, 1997), learning disabilities (Kerr & Hughes, 1987), and developmental coordination disorder (Smits-Engelsman, Wilson, Westenberg, & Duysens, 2003). To date, there are no studies of how children with heavy prenatal alcohol exposure co-regulate movement speed and accuracy during goal-directed movements and the purpose of the present study was to assess this interaction.

Given the extensive and diverse damage to the central nervous system (see Norman, Crocker, Mattson, & Riley, 2009, for a review of neuroimaging studies) and peripheral nervous system (Avaria, Mills, Kliensteuber, Aros, Conley, Cox, *et al.*, 2004) resulting from prenatal alcohol exposure, it was predicted that in comparison to a group of typically developing children, the prenatal exposure to alcohol group would produce significantly slower movement times which conform to a linear function described by Fitts' law, would experience reduced rates of information processing, and would show a higher percent of response errors.

Method

Participants

Children (7 to 17 years of age) with histories of heavy prenatal alcohol exposure were recruited from the Center for Behavioral Teratology at San Diego State University. Children had full scale IQ scores above 60 based on assessment with the Wechsler Preschool and Primary Scale of Intelligence, Third Edition (1991), and heavy prenatal alcohol exposure as estimated by retrospective use of social service records, medical records, and maternal responses to a standard questionnaire. Also, all participants were evaluated and screened for *in utero* alcohol exposure by Dr. Kenneth Lyons Jones, a dysmorphologist, using established criteria of specific facial anomalies (e.g., short palpebral fissures, underdeveloped philtrum, and short epicanthal folds), pre- and/or postnatal growth deficiency at or below the 10th percentile for either height or weight, and evidence of central nervous system dysfunction (Jones & Smith, 1973). Based on this screening process, the clinical group in the study comprised seven children with fetal alcohol syndrome and nine children with heavy prenatal

alcohol exposure. Initial statistical tests revealed no performance differences between these two subgroups, and they were combined into a single prenatal alcohol exposure group. Children with mental deficiency resulting from known causes other than prenatal exposure to alcohol and incomplete or unknown family history concerning prenatal alcohol exposure were not eligible to participate in the study.

Twenty-one typically developing children were recruited from the Center for Behavioral Teratology and served as a control group. These children were closely matched to the prenatal alcohol-exposed group for age, sex, and socioeconomic status (measured using the Hollingshead Four Factor Index of Social Status, 1975). Children in the control group also were evaluated with a comprehensive neuropsychological battery and screened for prenatal alcohol exposure and other teratogenic agents through a telephone interview and parental questionnaire that included retrospective information on alcohol consumption during pregnancy. Potential control participants were excluded from participation if more than minimal prenatal alcohol exposure was known or suspected or if alcohol exposure information was unavailable. Demographic information for the two groups is presented in Table 1. Informed consent and child assent were obtained prior to any assessment or testing in accord with institutional review board requirements.

Apparatus

The apparatus consisted of a pressure sensitive digitizing tablet (30.5×45.75 cm, resolution of 1,000 line per cm, acquisition rate 200 points per second, accuracy of pen placement 0.2 mm; Wacom, Inc., Vancouver, WA) placed on a table and inclined at 60° relative to the horizontal plane. The digitizing tablet was interfaced with a computer fitted with a 16-bit analog-to-digital converter (National Instruments, Austin, TX) that facilitated online data acquisition of the position of a stylus pen on the digitizing surface. A series of five target sheets was constructed, each set containing two red-colored, rectangular targets of uniform length (12.5 cm) on a white background. Target sets were defined by a specific combination of target width (in cm) and distance (in cm) between the target centers. These combinations of width and distance were as follows: Target Set 1, 2.5 and 5 cm; Target Set 2, 2.5 and 10 cm; Target Set 3, 2.5 and 20 cm; Target Set 4, 0.64 and 10 cm; and Target Set 5, 0.65 and 20 cm. These combinations produced values of task difficulty of 2, 3, 4, 5, and 6 bits of information, respectively, which represents a range from low to high movement difficulty.

Procedure

Each participant sat in a height-adjustable chair with the center of the right shoulder joint (left for left-handed children) equidistant from each target. Following a demonstration of the task, the participant held a stylus with the hand used for handwriting and tapped reciprocally between the two targets as rapidly and accurately as possible with a smooth and continuous arm action. The placement of the stylus tip relative to the target area was electronically monitored throughout each trial. Participants were asked to generate a response accuracy rate of 90 to 95% of total taps (Schmidt & Lee 2005), with placements of the stylus inside and outside the target area recorded as hits and misses, respectively. Participants were allowed a practice trial for each target set, followed by four test trials. Each trial lasted 17 sec. and the intertrial interval was 15 sec.

For each trial, the movement time between each tap and the number of misses were recorded online using a customized computer program based on LabView programming (National Instruments, Austin, TX). Limitations in computer software did not allow assessment of the movement end points relative to the target center and, therefore, data for the intra-participant distribution of movement errors about each target were not available. Data were collected at a sampling rate of 1 kHz and stored in spreadsheet format for analysis. The presentation

order of the target sets was counterbalanced across participants, and the interval between presentations of each target set was approximately 2 min. Testing required approximately 30 min. and a small monetary reward was provided at the end of the test session. Researchers were blind to group assignment during the testing and analysis phases of the study.

The reciprocal tapping test and another test (a single-finger tapping test with no spatial accuracy component or movement between targets) associated with another research project (Simmons, Thomas, Levy, & Riley, 2010) were completed in a single test session. The order of completing these two independent tests was counterbalanced across participants and the inter-test interval was 5 min., during which participants were free to stand and move about the area.

Analysis

Group comparisons on age, Full Scale IQ, socioeconomic status were separately assessed using *t* tests for independent samples. Internal consistency reliability for movement time was examined within each target set, and an intraclass correlation coefficient of .80 was used as the criterion of acceptable internal consistency (Nunnally & Bernstein, 1994). Percent of response misses (i.e., the number of misses divided by the total taps multiplied by 100), index of performance, and movement time were independently analyzed using analysis of variance (ANOVA) based on a 2 (group) $\times$ 5 (task difficulty) design with repeated measures on the second factor. Group (alcohol-exposed versus control) was the between-subjects factor, while task difficulty (2, 3, 4, 5, and 6 bits) was the within-subjects variable. For each participant, a linear function was fit to the movement time data, which yielded values for slope and R^2 (Smits-Engelsman, Rameckers, & Duysens, 2007). The slope (msec./bit) represents the change in performance speed as task difficulty increases and the R^2 value indicates goodness of fit of the regression line, i.e., the extent to which the linear function predicted by Fitts' law conformed to the data. The slope and R^2 values were separately analyzed using a one-way ANOVA with group (alcohol exposed versus control) as a between-subjects factor. For all analyses, age was entered as a covariate and assumptions of sphericity and homogeneity of variance were examined using Mauchly's and Levene's tests, respectively ($p < .05$). Any violations of sphericity prompted the use of the Greenhouse-Geisser conservative estimate of degrees of freedom and violations of homogeneity of variance invoked *post hoc* comparisons using Games-Howell procedures. Data were analyzed using SPSS Version 14.0. Alpha was set to .05.

Results

Group comparisons on age and socioeconomic status indicated no significant differences ($p > .05$), but children with prenatal alcohol exposure had significantly lower Full Scale IQ ($t = 4.65$, $p < .001$), which is characteristic of this syndrome but is unrelated to reciprocal tapping performance (Kennedy, Clement, & Curtiss, 2003).

Performance measures for the two groups as a function of task difficulty are presented in Table 2. Percent errors did not change significantly with task difficulty ($p > .05$), but the prenatal alcohol-exposed group produced significantly higher percent errors collapsed across levels of task difficulty than the control group ($F_{1,32} = 5.38$, $p < .03$; $\eta^2 = .14$).

Intraclass correlation coefficients for the two groups exceeded the *a priori* criterion of .80, so movement time data were averaged across trials for each target set. Analysis of movement time revealed a violation of sphericity, prompting the use of a conservative estimate of degrees of freedom to test group differences. Movement time was directly related to increasing difficulty ($F_{2,82,95,81} = 9.88$, $p < .001$; $\eta^2 = .23$). Pair-wise group comparisons of movement times for each level of task difficulty indicated no significant differences ($p > .$

05). The average slope value for the control and alcohol-exposed groups was 128.1 msec./bit ($SE = 9.8$) and 143.2 msec./bit ($SE = 11.3$), respectively, and these values were not significantly different ($F_{1,34} = 1.01$, $p > .05$). R^2 indexed how well each group's data conformed to the linear function predicted by Fitts' law. Analysis indicated no significant differences between the groups ($F_{1,34} = .001$, $p > .05$), with identical R^2 values of .91 for the two groups.

Analysis of index of performance as a function of movement difficulty and group indicated a significant main effect of target set ($F_{4,132} = 53.9$, $p < .001$; $\eta^2 = .62$). *Post hoc* comparisons indicated that when collapsed across groups, the index of performance significantly increased from relatively low values for task difficulties of 2 and 3 bits to higher values for task difficulties of 4, 5, and 6 bits. There was no group difference for index of performance ($F_{1,33} = 2.1$, $p > .05$; $\eta^2 = .05$).

Discussion

The study revealed that movement times produced by children with heavy prenatal alcohol exposure increased linearly with the logarithmic expression of task difficulty. That is, when co-regulating speed and accuracy to a stationary spatial target, movements of the children with prenatal alcohol exposure could be described adequately by Fitts' law. Also, adherence to the predicted linearity was high, as indicated by the mean regression coefficient for the group. The observed linearity of the movement time function is consistent with goal-directed movements of other syndromes involving central nervous system disorders. For example, movements of individuals with acquired brain injuries (Caeyenberghs, van Roon, Swinnen, & Smits-Engelsman, 2009) and movements of limbs affected by congenital spastic hemiplegia (Smits-Engelsman, *et al.*, 2007) also conformed to Fitts' law. However, unlike children with prenatal alcohol exposure, children with brain injury took approximately 22% longer than control children to complete movements; limbs affected by spastic hemiplegia (Smits-Engelsman, *et al.*, 2007) required about 80% more time to complete movements than unaffected limbs.

The present study is not the first to report comparable motor performance for children with and without histories of prenatal alcohol exposure. Young children with prenatal alcohol exposure between the ages of 13 and 24 months had the same motor skill competencies as nonalcohol-exposed children (Richardson, Day, & Goldschmidt, 1995), and there was no difference in gross motor skills during early childhood for children with or without prenatal alcohol exposure (Fried, O'Connell, & Watkinson, 1992). For children between 11 and 17 years of age, choice reaction time was equivalent for the two groups (Simmons, Thomas, Riley, & Levy, 2006).

The similarity of the groups' performances could be related to the use of a relatively small sample and associated reduced statistical power; but alternative explanations are plausible. Many daily functional tasks depend on successfully co-regulating movement speed and accuracy, and the similarity of results between the two groups may be based on the acquisition by children with prenatal alcohol exposure of sufficient motor experience to induce plastic changes, which translates into improved temporal-spatial regulation. Similar neural plasticity has been reported for typically developing individuals at the spinal cord (Curt, van Hedel, Klaus, & Dietz, 2008), cortex (Adkins, Boychuk, Remple, & Kleim, 2006), and cerebellar levels (Collin, Usiello, Erbs, Mathis, & Borrelli, 2004). Motor training also produced long-term neural reorganization in the cerebellum (Klintsova, Goodlett, & Greenough, 2000) and motor cortex (Klintsova, Dickson, Yoshida, & Greenough, 2004) of animals prenatally exposed to alcohol, especially when the motor training was complex in nature (Briones, Klintsova, & Greenough, 2004).

The similarity of the groups' movement times also could be associated with the prenatal alcohol group's sacrifice of spatial accuracy for movement speed. When collapsed across targets, the prenatal alcohol-exposure group had significantly higher percent errors than the control group. Reduced accuracy allows the former group to move between the targets at relatively normal speed.

Also assessed was the rate of index of performance or bandwidth (MacKenzie & Buxton, 1993) for the two groups, with higher bandwidth values representing higher performance. The relation between the index of performance and task difficulty is nonlinear, with initial increases in performance rates coupled with a leveling off in throughput rates for movements with difficulty values of 4 bits or higher (Target Sets 4 through 6). The data suggest a threshold of maximum information processing or the presence of a ceiling effect, but these notions require further evaluation since processing efficiency is selectively affected by prenatal alcohol exposure (Burden, Jacobson, & Jacobson, 2005).

In summary, the analyses demonstrate that goal-directed movements by children with prenatal alcohol exposure were performed in accordance with Fitts' law. The slope of the function between movement time and the logarithmic expression of task difficulty was linear and showed high adherence to the line of best fit. Further, the index of performance initially increased as task difficulty increased but leveled off when difficulty was equal to or greater than 4 bits of information. There were no differences between groups of children with or without heavy prenatal alcohol exposure for movement time, slope of the function, or index of performance.

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TABLE 1

Means and Standard Errors For Demographics For Children With Prenatal Alcohol Exposure and a Nonalcohol Control Group

	Prenatal Alcohol-exposed Group		Control Group	
	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>
Age, yr.	12.2	0.9	12.3	0.5
Socioeconomic status	47.0	3.2	47.0	2.1
Full Scale IQ	85.1	3.7	104.0	2.5

TABLE 2

Means and Standard Errors for Percent Error, Movement Time, and Index of Performance for Prenatal Alcohol Exposure and Control Groups and Internal Consistency Reliability (ICC) as a Function of Movement Difficulty

	Movement Difficulty (bits)											
	2		3		4		5		6			
	M	SE	M	SE	M	SE	M	SE	M	SE	M	SE
Errors, %												
Prenatal alcohol exposed	1.8	0.6	3.8	0.9	4.3	1.1	7.7	2.1	6.3	1.3		
Control	1.4	0.3	1.8	0.4	2.0	0.5	4.5	1.0	3.7	0.6		
Movement Time, msec.												
Prenatal alcohol exposed	403	32	475	32	561	39	779	42	966	41		
Control	357	28	442	33	560	34	716	36	868	36		
Index of Performance, bits/sec.												
Prenatal alcohol exposed	2.7	.2	4.4	.4	5.8	.4	5.6	.3	5.3	.3		
Control	3.1	.2	5.1	.3	5.7	.3	5.7	.4	6.1	.3		
Intraclass Correlation Coefficients (ICC)												
Prenatal alcohol exposed	.98		.96		.97		.95		.98			
Control	.99		.99		.97		.99		.99			