Published in final edited form as:

Otolaryngol Head Neck Surg. 2010 May ; 142(5): 708–714. doi:10.1016/j.otohns.2010.01.028.

Longitudinal posturography and rotational testing in children 3-9 years of age: Normative data

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Abstract

Objective—To obtain normative longitudinal vestibulo-ocular and balance test data in children from ages 3 to 9 with normal middle-ear status.

Study Design—Prospective, longitudinal cohort

Setting—Tertiary care pediatric hospital

Subjects and Methods—Three-year-old children were entered and tested yearly. Subjects underwent earth vertical axis rotation testing using sinusoidal and constant velocity stimuli and performed the Sensory Organization Test.

Results—One hundred forty-eight children were entered and usable data were collected on 127 children. A linear increase in the vestibulo-ocular reflex gain as children aged was found, without a change in the phase of the response. An age-related linear increase in Equilibrium Scores, indicating reduced postural sway, was also observed.

Conclusion—These normative data can be used in the evaluation of dizziness and balance disorders in children.

Introduction

A child with dizziness and/or balance dysfunction can present a complex diagnostic problem requiring a systematic approach that includes vestibular testing. A prerequisite for using

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Presented in part at ASPO, Nashville TN, May 2-6, 2003

Sponsorships or competing interests that may be relevant to content are disclosed at the end of this article.

vestibular test results in children as a clinical tool is the availability of age-appropriate normative data. Normal responses to both sinusoidal and constant velocity earth vertical axis rotations have been reported in children ranging in age from less than 1 year to 16 years.¹⁻⁵ In several of these studies, the gain of the VOR response decreased in older children.^{1,2,4} However, in other studies, VOR gain showed very little change as a function of age.^{3,5,6}

A test that is routinely employed during evaluation of adults with dizziness and balance disorders and is also used in children is the Sensory Organization Test (SOT), which assesses the use of vision, somatosensation and vestibular sensation for maintaining standing balance. Normative values for the SOT have been published for children aged 3 to 15 years, with studies showing larger sway in the youngest children, with a linear reduction in sway as children mature.^{7,8}

One consideration in the interpretation of these normative data is that middle-ear status was not evaluated at the time of testing. Eustachian tube dysfunction with and without otitis media with effusion (OME) is considered the most common cause of balance disturbances in children.⁹ Subjects with OME have been shown to have increased vestibular dysfunction,¹⁰ and increased postural sway during dynamic posturography.¹¹ Another consideration is that most of the previous reports of rotational data present cross-sectional data and have relatively small sample sizes; therefore it is not clear what changes occur in the rotational VOR and SOT responses in the same group of children as they develop. Consequently, the overall objective of this study was to obtain normative longitudinal vestibulo-ocular and balance test data in a large cohort of children from age 3 through 9 years with normal middle-ear status at the time of testing.

Methods

Population and Enrollment

This collaborative study was conducted at the Ear Nose and Throat Research Center (ENT-RC) Clinic at the Children's Hospital of Pittsburgh (CHP) and the Center for Balance Disorders (CBD) at the Eye and Ear Institute (E&EI) of Pittsburgh. Normal healthy children between ages 2 and 3 years, followed longitudinally since early infancy in one of two different epidemiologic studies, were recruited for enrollment in the present study.^{12,13} Additionally, some younger siblings of participants in those studies were enrolled. Informed consent for the child to participate in the study was obtained. The study was approved by the CHP Human Rights Committee and the University of Pittsburgh Institutional Review Board (2005 and after).

Children were excluded from entry if they had any of the following conditions: neonatal asphyxia or other serious illness; major congenital malformation including external, middle or inner ear or other major abnormality; sensorineural hearing loss; meningitis; labyrinthitis; temporal bone fracture; neurologic disease; epilepsy or severe head trauma; ear surgery, i.e. tympanoplasty, tympanomastoidectomy or tympanostomy tube insertion prior to age 2 years, cholesteatoma or chronic mastoiditis; intratemporal or intracranial suppurative complications of otitis media; use of ototoxic medication (except for topical use) and unreliable historical information or inadequate comprehension or cooperation.

A total of 148 children were enrolled in the study. For various reasons, data for 21 of the enrolled subjects were not able to be used, leading to a final data set of 127 children (70 males and 57 females). The reasons included non-compliance with instructions, fear of closing eyes during posturography, and fatigue from testing. The demographics of the final sample are shown in Table 1. No subjects had middle-ear effusion at the time of testing.

Procedure

Yearly testing

Children underwent balance and vestibular testing at yearly intervals from age 3 to 9 years. A history regarding the child's experience with otitis media was obtained. The child's height and weight were recorded.

An ear, nose and throat examination including pneumatic otoscopy was performed as well as tympanometry to assess middle-ear status. Only children deemed to be effusion-free underwent the yearly balance and vestibular testing. If a child was noted to have MEE when examined prior to testing, they were treated or observed (as necessary) until they could later be confirmed to not have MEE, at which time they were tested.

Behavioral audiometry and ophthalmologic screening were also performed yearly. The vestibular testing -- rotational testing and moving platform posturography testing were adapted to the age of the child and the child's ability to cooperate.

Definition of middle-ear effusion

Middle-ear effusion (MEE) was used to designate middle-ear disease diagnosed as either otitis media with effusion (OME) or acute otitis media (AOM). OME was defined as asymptomatic MEE, i.e., without the symptoms of inflammation found in AOM. The determination of the presence or absence of effusion was based on a previously described decision tree algorithm that combined immittance testing and pneumatic otoscopy by a validated otoscopist.¹⁴

Pneumatic Otoscopy and Immittance Measurement

Pneumatic otoscopy was performed by a validated otoscopist. Acoustic immittance testing was obtained using a GSI-38 Middle Ear Analyzer (Grason-Stadler, Inc., Milford, NH).

Vision screening

From age four years an ophthalmologic screening evaluation, using the Pre-School Vision Test and for older children the Snellen Vision Test, was performed at the time of yearly vestibular testing to exclude moderate to severe impairment of vision.

Vestibular Function Testing

The vestibular function tests performed included vestibulo-ocular testing (rotation) and vestibulo-spinal testing (moving platform posturography). Only children whose middle-ear status at the time of testing was judged to be normal and who were tested within three months of their birthday are included in the data analysis. Not all tests could be performed in their entirety on all children at each session, as the children were tested at many conditions and it was difficult to maintain the attention of the young children during all test conditions.

i. Rotational Testing

Rotational vestibular testing was performed using an earth vertical axis rotational device. The chair in which the child was seated was designed for safety and proper coupling of the rotational stimulus to the child's head, and thus his or her horizontal semicircular canals. Children were kept alert during testing by having them perform age-appropriate verbal alerting tasks. The rotational stimulus consisted of harmonic angular motion at several sinusoidal frequencies: 0.02, 0.05, 0.1 and 0.5 Hz, with a peak velocity of 50 deg/s. The .01 test was not performed because it would have taken an excessively long time (100 sec per cycle) and maintaining alertness would have been nearly impossible. During rotation, vestibular-induced eye movements were

recorded by electro-oculography (EOG) or video-oculography (VOG) with the child's eyes open behind opaque goggles. Three parameters were derived from the rotational testing: gain (the ratio of response magnitude to stimulus magnitude), phase (timing between the stimulus and response), and symmetry (mean value of the slow component eye velocity). Furthermore, a first-order model of the frequency response was estimated from the gain and phase data recorded at 50 deg/s velocity and 0.02 to 0.5 Hz frequency range. The estimated parameters of the transfer function were the sensitivity and time constant.

Rotational testing was also performed during constant velocity testing (60 deg/s). The sensitivity and time constant were estimated during clockwise and counter clockwise rotations. No difference in sensitivity or time constant was found between clockwise and counter-clockwise rotations; thus the values from both directions were averaged.

ii. Computerized Dynamic Posturography

The Sensory Organization Test (SOT) was performed using the EquiTest™ device (NeuroCom, Int. Clackamas, OR). This technique allows an assessment of the postural stability with and without the influence of vision and proprioception. The child stood on the platform safely attached with a harness to prevent him/her from falling. The visual surround consisted of a frontal wall and two lateral walls encompassing the entire peripheral visual field approximately 1 m from the child. The child was tested during six different standard sensory conditions: A) fixed support, SOT1= normal vision, SOT2= absent vision, and SOT3= sway-referenced vision; B) sway-referenced support, SOT4= normal vision, SOT5= absent vision, and SOT6= sway-referenced vision. Three trials lasting 20 s each were performed for each condition. Each child's postural sway for the six standard sensory conditions was recorded quantitatively by monitoring the forces exerted on the platform by their feet. These foot forces were digitized and converted to center-of-pressure (COP) estimates. Normalized Equilibrium Scores based on peak-to-peak sway, including the weighted average composite, were computed. The best score from each condition was selected for the statistical analysis. If a fall occurred on all three trials, a 0 was recorded for that condition. Standard Equitest software prohibits analysis of individuals who weigh less than 18 kg. Therefore, special software was used for children whose weight was less than 18 kg at the time of testing, which overrode this constraint.

Statistical Methods

For normative data, mean and standard deviations were calculated across years 3 to 9 for rotational testing and years 4 to 9 for posturography. We fitted a hierarchical linear model using the SAS MIXED procedure (SAS Institute, Inc., Cary, North Carolina) with each outcome (e.g. rotational gain at 0.05 Hz, SOT condition 1) as the dependent variable; age as the primary fixed effect of interest; subject-specific intercepts and slopes as random effects; and an unstructured correlation matrix. Sensitivity of the results to the use of this model was assessed by employing a standard mixed modeling strategy for the mean with each outcome as the dependent variable, age as the primary fixed effect of interest, and a subject random effect to account for the multiple measurements from the same set of subjects over time, and the resulting stochastic non-independence (data not shown).

In order to determine if gender had an effect on the rotation tests and posturography, at each nominal age from year 3 to 9, t-tests were performed with gender as a main effect. To examine whether there was a relationship between height and the dependent measures, Pearson's correlation coefficients were calculated.

Results

Rotational testing

The measured gain and phase from the sinusoidal chair rotations are displayed in Tables 2 and 3, respectively. At each frequency, the VOR gain increased linearly as a function of age, by about 0.05 to 0.06 per year ($p < 0.0001$). At 0.02, 0.05, and 0.1 Hz, there was no significant effect of age on the phase. However, at 0.5 Hz, phase decreased with a significant linear trend as children aged from 3 to 8 years ($p < 0.0001$). From these gain and phase data, a first-order model of the sensitivity and time constant were estimated (Table 4). The sensitivity increased linearly as a function of age, at a rate of 0.05 per year ($p < 0.001$). Likewise, the sensitivity estimated from the constant velocity rotations increased linearly at a rate of 0.08 per year ($p < 0.001$, Table 5). Furthermore, the sensitivity estimates from sinusoidal and constant velocity rotations were significantly correlated ($r^2 = 0.48$, $p < 0.001$). The estimated time constants showed little variation as a function of age, and were consistent for both types of tests.

Posturography

The fall rates and mean Equilibrium Scores for the six different sensory test conditions according to age are shown in Tables 6 and 7. Normative data obtained in healthy adults are included in Table 7 for comparison. During conditions 1 through 4, falls are a rare event at each age (Table 6). In conditions 5 and 6, especially during condition 6, fall rates increase for children aged 4 to 7. The mean Equilibrium Scores increased linearly as a function of age (Table 7, $p < 0.001$), although in some cases, the increase was not monotonic (e.g. a decrease in condition 5 from age 7 to 8). A comparison with normative adults values shows that by age 9, the equilibrium scores of children remain below those of adults. In Table 8, equations are provided for estimating posturography scores between the ages of 4 to 9. The amount of increase in the scores per condition ranges from 1.9 to 3.9 units per year.

Sex and Height

The effect of sex on the rotational and posturography testing was also investigated. Males and females did not demonstrate significantly different estimated sensitivities for either rotational test. However, on several of the sensory test conditions, females had significantly greater Equilibrium Scores (all $p < 0.05$). This occurred during condition 1 at ages 4 and 7; condition 2 at ages 4, 6, 7 and 9; condition 3 at age 8 and condition 5 at age 4. There was no significant relationship between height and rotational sensitivity and between height and Equilibrium Scores at any year of testing.

Discussion

The development of the vestibular end organ and myelination of the first order vestibular afferents is thought to be complete and functional at birth.¹⁵ However, the maturation of the VOR continues to develop after birth since many of the parameters of the VOR continue to change throughout childhood. Several groups have observed a decrease in constant velocity rotational gain as children aged from 3 months to 15 years.^{1,2} In studies utilizing sinusoidal rotational stimuli, these maturational trends have not been as evident, with level gains,^{3,5,6} and reduced gains,⁴ as children aged. In contrast, we found a linear increase in VOR sensitivity from 3 to 9 years for both constant velocity and sinusoidal rotational tests. A simple explanation for the discrepancy between our results and some of those in the literature is not obvious. Perhaps the limited cross-sectional samples, with relatively few subjects at each year (i.e. less than 15 per year) did not generalize to the overall population. A strength of our longitudinal study is in the ability to model within-subject changes as the children develop. Furthermore, variation in the testing technique (e.g. frequency of sinusoidal rotation or speed of constant

velocity rotation) or age of the subjects may account for the differences between our findings and those in the literature.

One possible contribution to the increased gain as a function of age found in this study may be an effect of attention. Mental alertness plays a key role in VOR function, as the VOR gain decreases with reduced levels of alertness.¹⁶ We kept our subjects alert during testing with age-appropriate tasking. However, changes in gain over the age range in our longitudinal study may be related to maturation of attentional mechanisms as part of the overall process of maturation of the vestibulo-ocular system.

With respect to the estimated time constant of the VOR, the data show a relatively stable response across 3 to 9 years, ranging from 13 to 17 seconds. These values of time constant are similar to those reported in the literature, ranging from 16 s in 7-12 year olds,⁴ to 11-19 s in 3 to 6 year olds.⁶ Moreover, these values are consistent with normative adult data for sinusoidal rotations (15 ± 15 s).¹⁷ These data suggest that the dynamic characteristics of the VOR reach mature levels by 3 years of age. It is of interest that the sensitivity of the VOR but not the dynamics of the VOR changed with increased age. This finding suggests that the maturation of the VOR was related to changes in that aspect of the VOR that controls the magnitude of the response but not its timing. Mathematical models of the VOR include both a gain element and a "velocity storage" element.¹⁸ The results of the study suggest that the velocity storage component of the VOR has already matured by early childhood because the dynamics of the VOR in childhood are essentially the same as those in adults. Thus the gain element of the VOR, independent of velocity storage appears to be the locus of change in the maturing VOR.

Postural stability during upright stance is maintained by the integration of sensory information provided by the visual, proprioceptive, and vestibular systems through an intricate feedback control system. In conditions 1 through 4, falls were rare events. In condition 5 (sway-referenced platform, eyes closed), fall rates were elevated in 4 year-olds compared with children ages 5 through 9. In condition 6 (sway-referenced platform and sway-referenced visual surround), fall rates were greater at ages 4 and 5. These findings suggest that the ability of younger children to use vestibular sensation as the primary modality, or to select the most appropriate feedback is continuing to develop.¹⁹

We found a linear increase in Equilibrium Scores as a function of age across all sensory conditions. This finding is consistent with several other reports of sensory organization testing in children.^{7,20} The presence of a statistical linear effect does not exclude the possibility that the development of the sensory control of posture occurs during transitional periods.²¹ In fact, the review of equilibrium scores in individual subjects shows considerable variation in the overall rate of change in the scores across subjects, as well as variation in the rate of change from year-to-year.

Our sample of children aged 4 to 9 years demonstrated reduced scores, i.e., increased sway, in the fixed-platform eyes-closed condition compared with adults, similar to the findings of Rine et al⁸ and Hirabayashi and Iwasaki.²⁰ Furthermore, we observed a greater decrement in scores relative to normative adult data in conditions 4, 5, and 6 (i.e. sway-referenced platform) compared with conditions 1, 2, and 3. The elevated postural sway generated during these conditions of erroneous proprioceptive feedback reinforces the idea that children respond inappropriately to conflicting sensory conditions.^{11,19}

Study limitations

The total number of tests performed at each age varied considerably, due to several reasons. Not all subjects attended the testing session every year and some test data were not usable due to technical problems. During the rotational tests, the number of invalid tests did not vary

according to age. Reasons given for not performing all rotational tests on all occasions included: subject-related factors (child unable to sit quietly, child fatigued, child feeling sick) and equipment-related factors (equipment failure, and use of alternate rotation chair). The constant velocity rotational tests were performed less frequently than the sinusoidal tests. One reason for this is that constant velocity tests were performed last, so if a child-related disruption occurred, it resulted in elimination of the constant velocity tests. Another reason is that when the alternate rotational chair was used, only sinusoidal tests were performed at 0.02 and 0.05 Hz.

During the posturography tests, the number of invalid tests decreased monotonically from 32 out of 83 at 3 years to 0 out of 18 at 9 years. There were less missing data for the SOT compared with the rotational chair tests. However, reasons given for not performing the SOT reflected subject-related factors (child fearful of closing eyes, child fearful of machine, and child unable to stand quietly).

Acknowledgments

We would like to thank the children in the study and their families. Without their commitment the study would not have been possible. We would also like to acknowledge the contribution of our colleagues: Kathy Tekely RN, Pat Fall CRNP and Children's Community Pediatrics -- Armstrong (Harold A. Altman MD, Kenneth R. Keppel MD, Thomas G. Lynch MD, JoAnn Nickleach MD, Donald J. Vigliotti MD, James K. Greenbaum, MD, Tracy Balentine RN) for their help in recruiting and following subjects; Anita Lieb and Susan Strelinski for performing the testing; and Howard Rockette PhD and Marcia Kurs-Lasky MS for their help in data management.

Supported by NIH grant 1RO1 DC2490-01A1 and GCRC grant M01-RR00084.

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Table 1

Demographics at entry of subjects who had valid test data (N = 127)

Demographic	N (%)
Gender	
Male	70 (55%)
Female	57 (45%)
Race	
Caucasian	97 (76%)
African-American	25 (20%)
Bi-racial	5 (4%)
Maternal Education	
< High school	4 (3%)
High school graduate/trade or tech school	111 (87%)
College	9 (7%)
Unknown	3 (2%)
History of tube insertion	
	3 (2%)
History of adenoidectomy or tonsillectomy	
	1 (1%)
Other children (≤ 12 years old) in household	
0	33 (26%)
1	49 (39%)
2	24 (19%)
3	14 (11%)
≥ 4	7 (6%)
Daily environment	
Home with parent/caregiver	97 (76%)
Daycare, 2-5 children, full-time	5 (4%)
Daycare, 2-5 children, part-time	3 (2%)
Daycare, > 5 children, full-time	15 (12%)
Daycare, > 5 children, part-time	2 (2%)
Pre-school	5 (4%)
Tobacco smoke exposure in household	
	47 (37%)

Table 2

Measured mean (SD) VOR gain estimated from sinusoidal rotational chair data obtained at 50 deg/sec at 0.02, 0.05, 0.1 and 0.5 Hz.

Age	0.02 Hz	0.05 Hz	0.1 Hz	0.5 Hz
3	0.44 (0.12)	0.48 (0.13)	0.53 (0.13)	0.58 (0.15)
4	0.48 (0.16)	0.57 (0.15)	0.59 (0.17)	0.64 (0.18)
5	0.50 (0.15)	0.61 (0.18)	0.64 (0.16)	0.66 (0.18)
6	0.56 (0.15)	0.70 (0.20)	0.73 (0.21)	0.72 (0.21)
7	0.66 (0.14)	0.74 (0.12)	0.75 (0.14)	0.78 (0.14)
8	0.69 (0.18)	0.77 (0.19)	0.76 (0.16)	0.82 (0.11)
9	0.72 (0.10)	0.75 (0.12)	N/P	N/P
	$y = 0.27 + 0.051^* \text{Age}$	$y = 0.37 + 0.049^* \text{Age}$	$y = 0.39 + 0.052^* \text{Age}$	$y = 0.44 + 0.047^* \text{Age}$

N/P: Tests were not performed at these frequencies for subjects at age 9.

* Equations for estimating the VOR gain at each frequency of stimulation, based on age in years, are provided for each significant relationship. All coefficients were significantly different from 0 ($p < 0.0001$).

Table 3

Measured mean (SD) VOR phase (in degrees) estimated from sinusoidal rotational chair data obtained at 50 deg/sec at 0.02, 0.05, 0.1 and 0.5 Hz

Age	0.02 Hz	0.05 Hz	0.1 Hz	0.5 Hz
3	22 (12)	10 (7)	8 (6)	1 (4)
4	26 (9)	11 (6)	8 (6)	2 (5)
5	25 (9)	11 (7)	8 (5)	0 (3)
6	27 (7)	12 (4)	8 (5)	0 (5)
7	26 (5)	12 (5)	4 (4)	-3 (3)
8	26 (6)	11 (5)	6 (5)	-4 (3)
9	22 (8)	13 (4)	N/P	N/P
$y = 5.7 - 1.1^* \text{Age}$				

N/P: Tests were not performed at these frequencies for subjects at age 9.

* The equation for estimating the VOR phase, based on age in years, is provided for 0.5 Hz. The intercept and slope coefficients were significantly different from 0 ($p < 0.0001$).

Table 4

Estimated mean (SD) VOR sensitivity and time constant in seconds from model fits of rotational chair data obtained at 50 deg/sec at 0.02, 0.05, 0.1 and 0.5 Hz.

Age	N	Sensitivity	Time Constant
3	24	0.52 (0.12)	17 (7)
4	45	0.61 (0.15)	16 (8)
5	53	0.62 (0.16)	17 (9)
6	37	0.71 (0.17)	16 (6)
7	17	0.76 (0.12)	16 (5)
8	24	0.79 (0.14)	17 (6)
$y = 0.38 + 0.053 * \text{Age}$			

* The equation for estimating the VOR sensitivity, based on age in years, is provided. The intercept and slope coefficients were significantly different from 0 ($p < 0.0001$).

Table 5

Estimated mean (SD) VOR sensitivity and time constant in seconds from constant velocity rotational chair data obtained at 60 deg/sec.

Age	N	Sensitivity	Time Constant
3	10	0.33 (0.18)	13 (6)
4	25	0.47 (0.21)	16 (5)
5	40	0.56 (0.24)	14 (5)
6	32	0.63 (0.21)	15 (4)
7	10	0.73 (0.24)	17 (8)
8	20	0.77 (0.21)	15 (3)
$y = 0.11 + 0.087^* \text{Age}$			

* The equation for estimating the VOR sensitivity, based on age in years, is provided. The intercept and slope coefficients were significantly different from 0 ($p < 0.0001$).

Table 6
Number of falls (% of subjects) during posturography as a function of age and test condition.

Age	N	SOT1	SOT2	SOT3	SOT4	SOT5	SOT6
4	51	0	1 (2)	0	1 (2)	10 (20)	13 (25)
5	76	0	0	0	2 (3)	4 (5)	19 (25)
6	74	0	0	0	0	6 (8)	11 (15)
7	69	0	0	0	1 (1)	4 (6)	10 (14)
8	38	0	0	0	1 (3)	2 (6)	2 (6)
9	18	0	0	0	0	2 (11)	3 (17)

SOT – Sensory Organization Test

Table 7

Posturography mean scores (SD) as a function of age and test condition, not including fall data. Adult reference group (n = 26) from Hirabayashi and Iwasaki (1995).

Age	N	SOT1	SOT2	SOT3	SOT4	SOT5	SOT6	SOT Comp
4	51	79 (7)	74 (11)	74 (9)	52 (13)	38 (15)	40 (15)	56 (8)
5	76	84 (7)	77 (8)	76 (13)	55 (15)	40 (16)	42 (16)	60 (9)
6	74	85 (6)	80 (8)	78 (8)	62 (14)	43 (15)	46 (16)	64 (8)
7	69	86 (7)	81 (9)	82 (7)	62 (14)	47 (15)	48 (16)	66 (9)
8	38	87 (7)	84 (6)	80 (7)	64 (17)	44 (13)	40 (19)	66 (8)
9	18	90 (7)	86 (5)	85 (7)	61 (19)	57 (14)	54 (18)	69 (11)
Adult	26	93 (2)	92 (4)	88 (5)	83 (11)	64 (11)	59 (15)	76 (7)

SOT – Sensory Organization Test

Table 8

Relationship between age and posturography score for different tests conditions.

Test Condition	Equation
SOT1	$y = 73 + 1.9^* \text{Age}$
SOT2	$y = 64 + 2.5^* \text{Age}$
SOT3	$y = 65 + 2.1^* \text{Age}$
SOT4	$y = 39 + 3.2^* \text{Age}$
SOT5	$y = 16 + 3.9^* \text{Age}$
SOT6	$y = 17 + 3.2^* \text{Age}$
SOT Comp	$y = 44 + 3.0^* \text{Age}$

SOT – Sensory Organization Test

* All coefficients were significantly different from 0 ($p < 0.003$).