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REVIEW

Music training and child development: a review of recent findings from a longitudinal study

Assal Habibi,[1] Antonio Damasio,[1] Beatriz Ilari,[2] Matthew Elliott Sachs,[1] and Hanna Damasio[1]

[1]Brain and Creativity Institute, Dornsife College of Letters, Arts and Sciences, University of Southern California, Los Angeles, California [2]Thornton School of Music, University of Southern California, Los Angeles, California

Address for correspondence: Assal Habibi, Brain and Creativity Institute, Dornsife College of Letters, Arts and Sciences, University of Southern California, 3620 A McClintock Avenue, Suite 262, Los Angeles, CA 90089-2921. assal.habibi@usc.edu

Evidence suggests that learning to play music enhances musical processing skills and benefits other cognitive abilities. Furthermore, studies of children and adults indicate that the brains of musicians and nonmusicians are different. It has not been determined, however, whether such differences result from pre-existing traits, musical training, or an interaction between the two. As part of an ongoing longitudinal study, we investigated the effects of music training on children's brain and cognitive development. The target group of children was compared with two groups of children, one involved in sports and another not enrolled in any systematic afterschool training. Two years after training, we observed that children in the music group had better performance than comparison groups in musically relevant auditory skills and showed related brain changes. For nonmusical skills, children with music training, compared with children without music or with sports training, showed stronger neural activation during a cognitive inhibition task in regions involved in response inhibition despite no differences in performance on behavioral measures of executive function. No such differences were found between music and sports groups. We conclude that music training induces brain and behavioral changes in children, and those changes are not attributable to pre-existing biological traits.

Keywords: music training; child development; inhibitory control; corpus callosum; magnetic resonance imaging (MRI); cortical thickness

Introduction

Over the past 2 decades, the consequences of learning to play a musical instrument on the cognition, socioemotional development, and status of brain structure and function in school-age children have been extensively investigated.[1,2] Playing music entails not only the recruitment of the auditory, somatosensory, and visual systems but also the interaction of these sensory systems with the motor, executive, and affective systems. The combination of such demands is likely to influence the differential development, maintenance, and function of certain brain structures. Several studies have reported anatomical and functional brain differences, as well as behavioral differences, when musicians are compared to nonmusicians (for comprehensive reviews, see Refs. 3–5).

Learning to play music, as one might expect, has been found to be positively associated with enhanced skills in the auditory domain, including frequency discrimination within the typical pitch range for music,[6] perception of pitch in speech,[7,8] recognition of an unfamiliar melody,[9] and detection of whether a sequence of chords ends correctly based on Western classical music rules.[10] In parallel, structural and functional brain differences have been reported between musicians and nonmusicians in primary and secondary auditory regions,[3–5,11–17] as well as in sensorimotor areas.[3,5,18]

It has been suggested that music training also enhances nonmusical cognitive and executive function skills. Learning to play an instrument engages three components of executive function: inhibition, working memory, and cognitive flexibility.[19,20]

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Playing a musical instrument requires musicians to continuously switch between reading notes and translating them into meaningful sounds by monitoring and adjusting fine finger movements. Furthermore, when playing in a group, musicians have to attend to new and competing streams of auditory information from other performers as well as their own playing.[21] It is likely that mastering such skills can lead to improvements in nonmusical cognitive domains. Indeed, several studies have shown that individuals with music training outperform their musically untrained peers in tasks assessing executive function, including auditory working memory.[20,22] Duration of music training has also been associated with better performance on auditory and visual forms of the Stroop tasks.[21,23,24] Some of these findings have not been replicated, however.[25,26] Structural brain differences between musicians and nonmusicians have also been reported outside of auditory and sensorimotor-related regions, including the inferior frontal regions[27–29] and multimodal integration regions.[11,30,31] Macro- and microstructural differences of the corpus callosum (CC)[32–34] have also been noted, suggesting that music-related anatomical changes can extend to brain regions that are not primarily engaged by the immediate sensorimotor demands of music-making.

In spite of a growing interest in the benefits of music training and in the brain differences of musicians compared with nonmusicians, the cause of such differences has not been made clear. The differences reported in cross-sectional studies might be due to long-term regular and intensive training. Still, they might result, partly or primarily, from pre-existing biological and genetic factors that predispose an individual to develop musical aptitude if exposed to music during a sensitive period of development. Here, as part of an ongoing 5-year longitudinal study on the effects of music training on neural, cognitive, and socioemotional development of children from deprived socioeconomic backgrounds,[35] we review the impact of music training after 2 years. We compare these children with control groups without music involvement but with the same socioeconomic and cultural backgrounds.[35] Here, we focus on musical and nonmusical skills and how they correlate with the development of specific brain regions.

Materials and methods

Participants

Seventy-five children (ages 6–7) were initially recruited from public elementary schools and community music and sports programs within low-income communities of the greater Los Angeles area. Between the initial induction and the time of this review, seven participants (two music, one sports, and four controls) discontinued their participation, in the study or their respective program. Twenty-one of the children had enrolled and were about to begin their participation in the Youth Orchestra of Los Angeles at Heart of Los Angeles program (hereafter called "music group"). The program is based on the Venezuelan system of musical training known as *El Sistema* and offers free music instruction 6–7 h weekly to children from underprivileged and low-income areas of Los Angeles. The program emphasizes ensemble practice and group performances and playing string instruments (violin and viola). Children applying to this program are selected, by lottery, up to a maximum of 20 per year, from a list of interested families. Twenty-three children formed the first control group who had enrolled and were about to begin training in a community-based soccer program or a community-based swimming program and were not engaged in any musical training (hereafter called "sports group"). The soccer program offers free soccer training three times a week with an additional game each weekend for children aged 6 and older; the swimming program offers free swimming instruction twice a week to school-age children with an additional recreational swimming session each weekend. Participants in both sports programs enrolled voluntarily in their respective programs, and both programs were taught by trained coaches. Twenty-four children formed the second control group (hereafter called "control group"). Children in this second control group were recruited from public schools in the same Los Angeles area, provided they were not involved in any systematic and intense afterschool program. All participants came from equally underprivileged backgrounds, with family incomes predominately below the federal poverty guidelines, and resided in geographical regions of Los Angeles affected by common problems of large urban areas, like high levels of poverty, drug trafficking, and violence. Most child participants were of Latino background and were being raised in bilingual households. They attended English-speaking schools that did not offer comprehensive music or sports education programs. At all assessment times, participants were screened by interview with their parents to ensure that they did not have any diagnosis of developmental or neurological disorder. The parents also answered an extensive structured interview on family income, education and ethnicity, perceptions of child's academic achievement and school participation, the child's current and previous participation in extracurricular activities, including involvement in sports or music programs, and the presence of any professional artists currently living in the child's home.

Procedures

Study protocols were approved by the University of Southern California Institutional Review Board. Informed consent was obtained in writing, in the preferred language, from the parents/guardians on behalf of the child participants, and verbal assent was obtained from all individual children. Either the guardians or the children could end their participation at any time. Participants (parents/guardians) received monetary compensation for their child's participation, and children were awarded small prizes (e.g., toys or stickers).

Behavioral assessments

Children were tested individually on a behavioral battery and completed two sets of assessments, 2 years apart. We will refer to time 1 as baseline assessment and time 2 as the assessment 2 years later. Testing sessions took place at the afterschool community center for the music group and at our laboratory in the Brain and Creativity Institute at the University of Southern California for the control groups. All children were assessed with the full battery.

Wechsler abbreviated scale of intelligence

The Block Design, Vocabulary, Matrix Reasoning, and Similarities subtests from the Wechsler Abbreviated Scale of Intelligence (WASI-II) were administrated at times 1 and 2.[36] In addition to these subtests, children were assessed, at both times, with the Memory for Digit Span task (forward and backward).

Gordon's measures of music audiation

The Gordon's Primary and Intermediate Measures of Music Audiation were used at times 1 and 2, respectively, as a measure of music aptitude.[37]

Behavioral color–word Stroop task

The color–word Stroop task, administrated at time 2 only, was designed to assess inhibition as measured by reaction time and accuracy.[38] During the task, children were presented with a word on a black screen written in one of four colors (red, yellow, green, or blue) and were instructed to name, aloud, the color of the stimulus, regardless of the meaning of the written word. Participants completed six separate blocks of the task, where each block consisted of 12 trials of either all congruent trials, (in which the color of word matched the written word), or all incongruent trials, (in which the color of word did not match the written word).

Tonal discrimination task

The tonal discrimination task was designed to assess music listening and pitch discrimination skills. The assessment was administrated at time 2 only, and it required participants to make a same/different judgment of two short musical phrases using a button press response (see 39 for details).

Imaging

Magnetic resonance imaging (MRI) sessions took place at the Dornsife Cognitive Neuroscience Imaging Center at the University of Southern California. The brain imaging sessions included anatomical T1 (MPRAGE) and diffusion and functional MRIs. As described earlier,[35] we designed a child-friendly protocol that included an extensive training session before the actual scanning session. High-resolution T1-weighted MPRAGE MRI images and diffusion images were acquired during times 1 and 2. Functional images were obtained only at time 2. During the functional scan, children performed the same color–word Stroop task modified to be used for young participants inside the scanner.[40] See Table S1 (online only) for a scheduled of administered tests at times 1 and 2.

Analysis

Performance on the behavioral tests for times 1 and 2 was calculated separately, and groups were compared using univariate ANOVAs with music, control, and sports as between factors. In the imaging analysis, change in cortical thickness and volume for

Table 1. Means, standard deviations, and statistics analysis for age and IQ at times 1 and 2, along with number of females and socioeconomic status (average maternal education and average household income) for music, sports, and control groups

Group	No. of female participants	Age at time 1	Age at time 2	Household income and maternal education	FSIQ-4 Time 1	FSIQ-4 Time 2
Music	8	79.6 (5.2)	104.2 (5)	\$10,000–19,999 High school graduate	100.1 (12.8)	102.4 (14.7)
Sports	11	82.9 (7.4)	106.8 (7.3)	\$10,000–19,999 High school graduate	95.4 (10.4)	96.6 (10.8)
Control	9	84.5 (5.9)	107.5 (5.8)	\$10,000–19,999 High school graduate	94.5 (10.7)	97.6 (12.4)
Statistical comparison	$\chi 2$ (2) = 0.63, $P = 0.72$	$F(2, 65) = 3.4$, $P = .004$	$F(2, 65) = 1.63$, $P = 0.2$	$F(2, 49) = 0.84$, $P = 0.43$	$F(2, 65) = 1.49$, $P = 0.23$	$F(2, 64) = 1.26$, $P = 0.28$

NOTE: There was a significant difference in age among the three groups, at time 1 where children in the music group were on average 5 months younger than the children in the control group (M versus C, $P = 0.03$). The age difference between children in the music and sports groups (M versus S, $P = 0.2$) or children in the sports and control groups (S versus C, $P = 0.6$) was not significant. At time 2, children in the music group were still on average 3.3 months younger than the children in the control group, although the main effect of age was no longer significant among the three groups. This was due to the interval between the two assessments; on average, it was 1.7 months longer for the children in the music than in the control group (music: 24.6 (1.2) months; sports: 23.9 (1.04) months, and control: 22.9 (0.96) months). There was no significant difference among the three groups in sex distribution, socioeconomic status, or IQ scores at time 1 or time 2.

each hemisphere and each individual a priori region of interest (ROI) were calculated using BrainSuite[41] (http://brainsuite.org/). A series of multivariate ANOVAs were used with music, control, and sports as between factors to compare the changes in cortical thickness and volume of the left versus the right hemisphere in selected ROIs (see Ref. 42 for details). BrainSuite Diffusion Pipeline (http://brainsuite.org/processing/diffusion/) was used for the analysis of diffusion MRI data. Mean and variance for fractional anisotropy (FA) and mean diffusivity (MD) values were computed for the whole CC and seven subdivisions.[42] Using a series of univariate ANOVAs with music, control, and sports as between factors, we compared FA and MD for scans 1 and 2 separately in the seven segments of the CC. Functional MRI data were analyzed using FSL (FMRIB's Software Library; http://fsl.fmrib.ox.ac.uk/fsl/fslwiki/). Following standard neuroimaging preprocessing, a general linear model was applied to model and contrast the blood oxygen level–dependent (BOLD) signal associated with incongruent blocks and congruent blocks of the color–word Stroop task. Individual subject-level models were then combined into a higher level to compare differences in brain activation during these contrasting conditions between the three groups. Percent change of the BOLD signal between the incongruent and congruent conditions within two ROIs, the inferior frontal gyrus and the supplementary motor area, was then correlated with behavioral measures collected outside of the scanner during tasks of cognitive control.[43]

Results and discussion

IQ, age, sex, socioeconomic status, and interval between the two assessment times were not included as factors in subsequent analysis (Table 1). Bilingualism was not included as a factor in analysis, because most participants (94%) were raised in bilingual households.

In relation to the structure and function of the brain, comparing time 1 (before music training) to time 2 (after 2 years of music training), we observed in all children some degree of cortical thinning over the whole brain, as expected in normal brain development at this age. However, there were differences between the children in the music group and the control groups in the auditory association area, as evidenced by a group × laterality interaction of the reduction of cortical thickness ($F(2,53) = 3.99$, $P = 0.024$, $\eta p^2 = 0.13$) and cortical volume (albeit not significant) ($F(2,53) = 2.44$, $P = 0.09$, $\eta p^2 = 0.08$); in other words, while the difference of reduction in cortical thickness and cortical volume between left and right posterior superior temporal

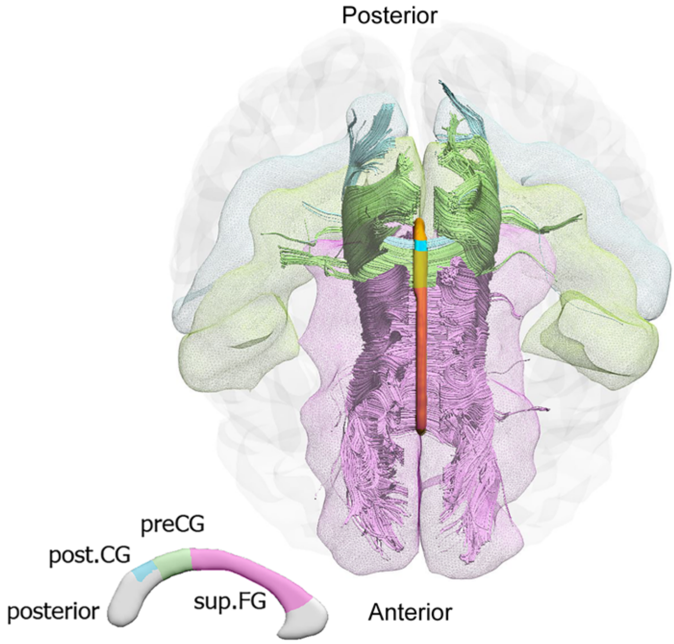

Figure 1. FA was increased at time 2 in the music group, compared with two control groups, in the connections between superior frontal gyri (pink), precentral gyri (green), and the postcentral gyrus (light blur) of the corpus callosum (seen from above).

gyrus was not different for the two control groups (sports and control), the music group showed a trend: larger reduction of thickness and volume of the left versus right posterior superior temporal gyrus. We did not uncover a correlation between performance on behavioral assessments and changes in cortical volume or cortical thickness.[42]

Second, at time 2, children with music training showed higher values in FA in three segments of the CC than the two control groups; the segments showing these differences correspond to crossing of fiber tracks connecting right and left postcentral gyri ($F(2,40) = 2.81$, $P = 0.07$, $\eta p^2 = 0.12$), precentral gyri, ($F(2,41) = 3.32$, $P = 0.04$, $\eta p^2 = 0.14$), and superior frontal gyri/supplementary motor area ($F(2,40) = 4.19$, $P = 0.02$, $\eta p^2 = 0.17$)[42] (Fig. 1).

Third, children with music training, compared with the children in the control group (those without any systematic training), showed a greater neural activity during the color–word Stroop task, specifically when incongruent trials were contrasted with congruent trials. This difference was observed in a network of brain regions that are known to be involved in response inhibition and includes the bilateral inferior frontal gyrus, supplementary motor area, anterior cingulate, precentral gyrus, and insula. No comparable significant difference was observed when the children with music training were compared with the children with sports training. Percent signal change in both the inferior frontal gyrus and the supplementary motor area was positively correlated with performance on a behavioral version of the color–word Stroop task that was completed outside of the scanner[43] (Fig. 2).

Finally, at time 2, after 2 years of training, children in the music group outperformed children in the two control groups in the tonal discrimination task ($F(2,61) = 5.007$, $P = 0.009$, $\eta p^2 = 0.14$; (M versus S, $P = 0.002$), (M versus C, $P = 0.08$), and (S versus C, $P = 0.15$)). The performance on the nonmusical behavioral tasks was not significantly different across the groups (Table 2).

Our findings are in line with previous reports of music training–induced structural and functional brain differences between adult musicians and nonmusicians, in particular with results pertaining to auditory processing and the respective auditory regions.[18,44] Given the cross-sectional nature of these studies, however, and the fact that they were carried out in adults, pre-existing genetic dispositions as well as the environment may have contributed to the findings. Still, we note that

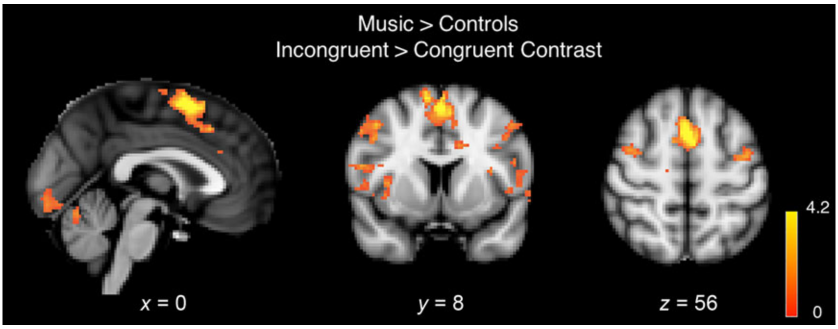

Figure 2. Whole-brain activation for incongruent versus congruent trials of the fMRI color–word Stroop task in a two-sample comparison of music group greater than control group. Red to yellow corresponds to positive Z-values. Images are cluster thresholded at $Z > 2.3$ and cluster size threshold of $P < 0.05$.

a prior longitudinal study of changes related to the learning of a musical instrument by Hyde and colleagues[45] demonstrated that 6-year-old children receiving instrumental musical training for 15 months showed improvements in musical tasks and had increased gray matter density in the right primary auditory cortex, while age-matched children receiving no musical training did not.

We have observed, as expected, an overall maturation-related decrease in cortical thickness in all children and in all ROIs; however, children with music training showed an asymmetric reduction of cortical thickness and volume in the posterior segment of the superior temporal gyrus (pSTG) (larger reduction on the left than on the right). The changes within the right pSTG in the music group were possibly due to an experience-dependent increase in cortical thickness—rather than a decrease—resulting from the frequent and systematic engagement of the right pSTG in the musical training processes. Consequently, we interpret the reduction in the rate of cortical thinning on the right versus left pSTG as related to the interaction of the normal course of cortical thinning of auditory association areas, with an increase in gray matter induced by early and intensive music stimulation. In brief, two competing forces, typical maturation of cortex and experienced-based changes, would be influencing the cortical thickness. Experience-based thickening of cortex has been previously shown in language-related areas.[46] In these studies, it was associated with fine-tuning and mastery of linguistic skills during late childhood. In our study, the children with 2 years of music training showed better performance in a tonal discrimination task than the children in the control groups, further supporting the interpretation that the asymmetric cortical thinning of the pSTG may be related to engagement of this region during the process of learning to play music.

We also showed that children with 2 years of music training have larger FA in the CC, specifically at the level of crossing fibers connecting superior frontal, sensory, and motor segments across the callosum, compared with the two control groups. These findings confirm previous reports in which musicians, compared with nonmusicians, have a larger CC and higher callosal connectivity, specifically at the anterior portion of the CC.[33] Given that playing a musical instrument requires bilateral cortical processing of sound, coordination of both hands, and integration of actions of auditory and motor systems, it is possible that these demands lead to a higher interhemispheric interaction between sensorimotor regions, which, in turn, would promote accelerated maturation of the connections that join them.

Contrary to their better performance on musical tasks, in the nonmusical cognitive tasks, children in the music group did not perform better or show more notable improvement than those in both control groups. We also did not observe any differences in cortical thickness or cortical volume between the music and control groups, outside of the auditory regions (e.g., in the inferior frontal gyrus). However, children with music training showed significantly greater neural activity during a color–word Stroop task in a network of brain regions that are known to be involved in response inhibition. These include the bilateral inferior frontal regions and the supplementary motor area. Playing a musical instrument requires using many of the same cognitive

Table 2. Means, standard deviations, and statistics analysis for performance on the behavioral measures for the music, sports, and control groups

	Gordon's measure Time 1		Gordon's measure Time 2		Tonal discrimination	Color–word Stroop	
Group/assessment	Tonal	Rhythm	Tonal	Rhythm	Hit rate	Accuracy	RT
Music	30.4 (5.3)	29.5 (3.9)	33.3 (4.7)	29.3 (4.3)	0.56 (0.18)	–0.08 (0.06)	313 (123)
Sports	30.1 (6.4)	27.8 (4.2)	32.4 (2.3)	28.3 (4.4)	0.35 (0.2)	–0.06 (0.04)	239 (146)
Control	30.4 (4.5)	26.8 (4.9)	33.1 (2.7)	28.6 (4.7)	0.44 (0.24)	–0.08 (0.11)	259 (113)
Statistical comparison	$F(2,61) = 0.02$ $P = 0.97$	$F(2,58) = 1.98$ $P = 0.14$	$F(2,61) = 0.66$ $P = 0.51$	$F(2,62) = 0.23$ $P = 0.79$	$F(2,61) = 5$ $P = 0.009$	$F(2,41) = 1.58$ $P = 0.21$	$F(2,41) = 1.18$ $P = 0.31$

mechanisms usually required for a variety of executive functions. While playing, a musician must continuously switch between reading notes, attending to new and competing streams of auditory information, and monitoring and adjusting necessary motor movements. Given the complexity of these requirements, it is not surprising that training-related changes are observed in brain regions involved in both auditory and other cognitive processes. It has indeed been proposed that, during musical training, modulations of inhibitory control, in particular, might mediate the transfer of skills from musical to nonmusical and cognitive abilities.[47]

It is also important to note that no differences were detected in inhibition-related activity during the Stroop task between groups of the children with music training and those with sports training. This suggests that participation in activities other than music may in fact be associated with such change in the cognitive organization involved in executive function, provided that the activities are socially interactive and comparably motivating and engaging.[48] Just like music training, learning to play sports requires focused attention, demands sensorimotor integration, and entails developing a skill via repeated practice and attention to the performances and needs of others in the group. Other mechanisms could additionally account for far-transfer nonmusical effects of both types of training, such as the self-discipline and self-motivation that is required to learn a new skill or the social interactions that come with working together to achieve a shared larger goal.

We also did not observe any significant differences in inhibition-related activity during the Stroop task between the sports group and the control group. In other words, performance of children in the sports group fell between the music and control groups. It may well be that music training influences executive function more strongly than sports training, but, given the sample size, the differences were only detectable on the extreme ends. It is also possible that the nonsignificant difference in inhibition-related brain activity between the music group and the sports group may be related to the longer duration and higher intensity of the music program, where children attended 6–7 h per week compared with the two sports programs, where children attended 3–4 h per week.

Because we are investigating young children during a period of intense change due to typical normal development, the short time of intervention—about 2 years—can be seen as a possible explanation for the current lack of differences detectable in brain areas beyond the auditory regions. It is likely that experience-based changes occur first in brain regions that are directly related to playing a musical instrument (i.e., auditory and motor); and changes in areas responsible for higher-level integration, planning, and execution may only surface at a later stage.

Given that there were no differences among the groups at baseline, before the onset of music and sports training,[35] our findings provide strong evidence that the observed differences favoring the music group are probably related to the music training rather than to pre-existing biological dispositions for musicality. We further note that additional neuroimaging data collection and behavioral assessments are currently underway as part of the still-continuing longitudinal study. We plan to report soon on our findings after 4 years of training.

Given that length of music training has been previously shown to correlate with changes in brain morphology in adult musicians,[34,49] we will be in a better position to comment on the differences between the music group and the two other groups after a longer period of observation. Still, it is fair to conclude that our findings already suggest that music training plays a significant role in childhood development at both behavioral and neural levels and that these findings concern children from disadvantaged backgrounds who would normally not have access to music instruction.

Competing interests

The authors declare no competing interests.

Supporting Information

Additional supporting information may be found in the online version of this article.

Table S1. Assessments administered at times 1 and 2.

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