How musicality, cognition and sensorimotor skills relate in

musically untrained children

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Abstract

Whereas a growing corpus of research has investigated the impact of music practice on several domains of cognition, studies on the relationships between musicality and other abilities and skills in musically untrained children are scarce. The present study examined the associations between musicality, cognition and sensorimotor skills in 69 musically untrained primary school children of around 10 years of age, using a test battery of musical, cognitive and sensorimotor abilities. We analyzed the results using non-parametric correlations and an exploratory factor analysis.

It was our anticipation that basic cognitive resources (short-term and working memory, attention, processing speed) would relate to both higher-order cognition and musicality.

Results indicated that, in musically untrained children, the interconnections between musical and cognitive abilities restrain to auditory short-term and working memory. Direct associations between musicality and higher-order cognitive processes did not occur.

An interesting secondary finding comprised associations between sensorimotor function, as measured by the Purdue Pegboard test, and higher-order cognition. Specifically, we found an association between bimanual coordination of fine finger dexterity, and matrix reasoning. This outcome suggests that higher-order cognitive function benefits from an efficient mastering of procedural aspects of sensorimotor skills.

Introduction

The present study explored the links between musicality, cognition and sensorimotor abilities in 69 musically untrained primary school children of around 10 years of age using an ad-hoc test battery of musical, cognitive and procedural abilities.

The human brain seems prewired for music processing, both concerning pitch (Perani et al., 2010) and rhythm (Winkler et al., 2009). Neonates responded in a specific right-sided brain network to well-structured dance music but not to scrambled versions of the same stimuli (Perani et al., 2010). Other newborns emitted mismatch-like responses to unexpected omissions of the strong beat within the measure (Winkler et al., 2009). These observations support the hypothesis, that universal aspects of musicality are innate and a basic ingredient of early perceptual and cognitive function and development (Hannon & Trainor, 2007).

More specifically, in early infancy, musical hearing and ability are supposed essential to language acquisition: "Without the ability to hear musically, we would be unable to learn to speak" (Brandt et al., 2012, p. 327). Brandt and colleagues argue compellingly that natural language and music development -the latter without explicit training- mature along similar tracks, both following enculturation by mere exposure (Hannon & Trainor, 2007). In 5- to 7-year-old children, interrelationships between language and music skills occurred, particularly if similar processes were involved like syntax processing (Cohrdes et al., 2016). Apart from links to language skills, however, few empirical data exist regarding the associations between musicality and more general cognitive processing abilities in musically untrained children. An awareness of musical syntax incongruity in simple and complex music manifested from as early as 6 years of age in both musically naïve and musically trained primary school children (James, Dupuis-Lozeron, et al., 2012). Additionally, in an EEG (electroencephalography) study, 16 musically untrained school children of around ten years of age, better detected musical transgressions with increasing auditory working memory scores (James et al., 2015).

Musical practice, i.e. actively playing an instrument or singing, covering a wide and diverse field of competences -ranging from sensorimotor to cognitive processing activities of the highest level- manifests as a driving force of cognitive and sensorimotor development. The impact of music practice on several domains of cognition, including language, is supported by a growing corpus of research (Anvari et al., 2002; Courey et al., 2012; Degé et al., 2011; James et al., 2020; Jaschke et al., 2018; Martins et al., 2018; Miendlarzewska & Trost, 2013; Moreno et al., 2009, 2011; Rauscher et al., 1997; Rickard et al., 2012; Roden et al., 2012, 2014; Rose et al., 2015; Schellenberg, 2004, 2006; Seither-Preisler et al., 2014). Although some methodological weaknesses may be present in these studies, partially because of lack of consensus on definitions of musicality and of transfer (Jaschke et al., 2013), it seems that, when practicing musical skill specifically and actively over longer time periods, links between musical and cognitive abilities become gradually entangled and enhanced. This observation supposes that certain basic cognitive processing resources are shared between general and musical cognition.

Research on the relationships between musical cognition and other domains in naturally developing non-musician children is still scarce. One study reported that the discrimination of musical rhythm predicted grammar skills in 6-year-olds (Gordon et al., 2015).

Findings are diverse on the relationship between cognition and sensorimotor skill. Two studies showed that the development of fine motor skills before the age of four does not predict cognitive performance during school age (Piek et al., 2008; Wang et al., 2014). In young adults, motor timing and abstract reasoning positively correlated (Lorås et al., 2013). In children between sic and nine years of age, performance on a visuomotor precision task was positively related to measures of intelligence (Mous et al., 2017), and in preschoolers, fine motor skills positively influenced lexical processing (Suggate & Stoeger, 2017).

Data are essentially lacking concerning the relationship between musical abilities and sensorimotor skill in non-musician children.

We conducted our study in public primary schools in popular neighborhoods in the vicinity of Geneva, with children of varying ethnic and socio-economic backgrounds. We explored how naturally developed musicality, i.e. by means of mere exposition in daily life, thus implicit learning, related to other domains, such as verbal memory and learning, processing speed, mental flexibility, attention, auditory memory, matrix reasoning and sensorimotor skills. This battery was composed of tests measuring abilities implied in musical, cognitive and sensorimotor activities that might potentially be associated.

Because possessing good discriminatory skills for pitch and rhythm is not sufficient to evaluate musicality, we adopted Karma's definition of musical aptitude (Karma, 2007) as representing "auditory structuring", expressing the capacity to group individual notes into gestalts and to form expectancies. To that end, we used a musical test that goes beyond mere examining of good auditory discrimination, namely, Gordon's Advanced Measures of Music Audiation, involving comparing musical phrases.

We analyzed the results by means of simple relationships between the scores of all different tests and also within an exploratory factor analysis.

The current study examined the following assumptions. First, we hypothesized that musical abilities are related to basic cognitive resources, namely, short-term memory, working memory, attention, processing speed and mental flexibility (Bergman Nutley et al., 2014; James et al., 2015, 2020; Roden et al., 2014). Second, we assumed that cognition and sensorimotor function may be related, since first expressions of intelligence are sensorimotor-related (Anderson et al., 2013) and simple but especially complex motor tasks demand good organization in time and space and thus some abstract reasoning (Lorås et al., 2013). Third, since musical experience is intrinsically related to sensorimotor behavior in non-musicians,

especially for rhythm perception (Chen et al., 2008; Grahn & Rowe, 2009; James, Michel, et al., 2012), musical performance in the rhythm perception domain and sensorimotor performance may correlate.

Methods

Participants

Sixty-nine primary schoolchildren participated in the study, with a mean age of 10.18 years (SD = 0.31; 41 girls). They all attended public schools in the Geneva canton, in French-speaking Switzerland. The group contained children of varying ethnic and socioeconomic backgrounds. The children had almost finished their sixth year of elementary school, which in Switzerland lasts approximately from age four to twelve years (eight consecutive years). One of the schools prohibited collecting precise information on the education level and actual professional occupation of the parents for ethical reasons that we can therefore not report here. We requested that none of the children who participated in the study, followed regular or protocolled music practice outside the school curriculum. Seven children were lefthanded.

The children and their caregivers signed an informed consent. The ethics commission of the Faculty of Psychology and Educational Sciences of the University of Geneva approved the protocol, in agreement with the ethical standards of the declaration of Helsinki.

Procedure

The experimenters, all Master's students at the Psychology Department of the University of Geneva, tested children individually. Testing took place within the schools, in specifically selected quiet rooms. First the experimenter explained the overall aim of the study: "You are going to participate in a study of the University of Geneva that investigates how children develop." They then encouraged the child to ask questions and emphasized that they may ask

for a break at any time.

All tests listed below (Table 1) were administered in pseudorandomized order, though the word vocabulary test was always presented relatively early, as a delayed word recall required a 50-min suspension.

Total testing time was less than 1 h and 30 min, spread over approximately 2 h, separated by breaks. Children enjoyed participating, and only a few complained about fatigue. They all received a small gift at the end of the session.

INSERT TABLE 1 ABOUT HERE

Materials

Table 1 lists all tests, measured variables, acronyms of the tests and involved abilities

Music Audiation

In order to assess general music processing, comprising the melodic and the rhythm domain, we administered the "Advanced Measures of Music Audiation" (AMMA; Gordon, 1989). This test does not require any prior musical knowledge or skills. It encompasses 30 trials consisting of pairs of musical melodies or phrases presented over headphones via the computer. The test can be applied to children from the seventh grade, without any prior musical training. For each pair the children judged whether the melodies were identical or different. If they considered the two melodies of the pair different, they had to express whether the difference was rhythmic or melodic. The test is constructed such that only one type of difference (melodic or rhythmic) may occur between the two melodies at a time. The experimenters noted the answers on an answer sheet. Because the scoring system penalizes errors, we encouraged the children not to respond if they were not sure what to answer. The answer sheet therefore contained four

columns: *identical – melodic difference – rhythmic difference – I don't know.* After an initial explanation of the concepts of melody and rhythm, and before the actual test, three training trials that did not appear in the final test were presented and discussed with the children to assure their comprehension of the instructions. We computed a tonal and a rhythmic score, according to the AMMA manual (Gordon, 1989), which involves subtracting points for wrong answers for both scores. From these scores we inferred percentile rank scores according to the AMMA manual, which we used for the analyses.

We do not report the composite score, which is a simple addition of both the tonal and the rhythm score and does not supply any additional information.

Matrix reasoning

Music cognition implies some abstract reasoning, as musical phrases evolve over time according to musical syntax, like language (Patel, 2012). In order to assess children's abstract reasoning skills, we administered the Matrices subtest of the WISC-IV (Wechsler, 2003). We presented different sheets with series of three images (e.g., three skateboards) to the children, whose task was to find the image that correctly completed the series (e.g., another skateboard) among four distractors (e.g., other toys). To familiarize the children with the task, we began with three practice trials. For the actual tasks, the sheets progressively increased in difficulty. Children worked on the task until they answered four out of five consecutive sheets incorrectly. The final score of Matrix Reasoning (MR) represents the number of correctly answered sheets.

Selective visual attention

To assess children's selective visual attention, we administered the D2 Test of Attention (Brickenkamp & Zillmer, 1998). For this task, we presented a sheet with 14 rows of 47 stimuli.

Stimuli were the letters d or p accompanied by one or two apostrophes above and/or below the letter. The children's task was to cross out all the d's that were accompanied by exactly two apostrophes (i.e., two apostrophes above, two apostrophes below or one above and one below the d) without crossing out any of the distractors (d's accompanied by only one apostrophe and all p's). To familiarize participants with the task, children first performed a practice row of 22 trials. For the actual task, children started working on the first row and were asked to switch to the next row every 20 s. The outcome measure (D2) provides the number of marked items minus the number of errors and omissions.

Visual processing speed and mental flexibility

To assess children's visual processing speed and mental flexibility, we applied the Children's Color Trails Test (CCTT) (Llorente, 2003), which consists of two subtests. For test 1 (CCTT-1), children were presented a sheet with 15 circles containing the digits "1" to "15." Their task was to connect the digits in increasing order. All circles with even digits were colored yellow, whereas the circles with odd numbers were colored pink. For test 2 (CCTT-2), the children had to perform the same task, except that for each digit (except for "1") two circles were depicted on the sheet, one colored yellow, the other colored pink. Thus, the children were instructed that, in addition to connecting the digits in increasing order, the colors of the circles would have to alternate for each digit (the pink "1" had to be connected with the yellow "2," which had to be connected to the pink "3," etc.). The first subtest evaluates simple visual processing speed, the second one also mental flexibility. To familiarize the children with the tasks, we began tests 1 and 2 with an 8-digit practice sheet. We computed standard scores as outcomes for both subtests (M = 100; SD = 15). For the analyses we used percentile scores.

Digit span forward and backward

In order to assess a measure of auditory short-term memory and working memory, the children accomplished the "digit span" subtest of the Wechsler Intelligence Scale for Children – Revised (Wechsler, 2005). During these tests, the children listened to recorded spoken series of digits with increasing length. We used prerecorded spoken series to assure a regular pace (1 s per digit) and identical pronunciation for all participants. The participants' task consisted of repeating the series orally, in the first task in direct, in the second in reverse order. Digit Span Forward (DSF) and Digit Span Backward (DSB) tasks assess distinct but interdependent cognitive functions (Grégoire, 2009). DSF evaluates essentially serial short-term auditory memory, whereas DSB evaluates the child's ability to manipulate verbal information while temporarily stored, thus principally working memory capacity. Two digits series (one for each task), progressively increasing in length and thus in difficulty, were presented. The children first performed the DSF (span size from 2 up to 9) then the DSB task (span size from 2 up to 8). They proceeded through the trials until they made two successive mistakes with the same number of digits, i.e., at the same level of difficulty. Each correct answer merits one point for a total of 16 points per task.

Rey Auditory Verbal Learning Test

The experimenters orally presented a list of 15 unrelated words to the children (Bean, 2011; Rey, 1964), repeated over five different trials. The task consisted of repeating as many correct words out of the list as possible after a short break of approx. 10 s. For the first trial, the time limit for recollection was set at 1 min, for trials 2–5 to 1 min and 30 s. The list was read aloud first every time. Trials 2–5 are performed immediately after trial 1. After a delay of approx.50 min, the child should once more cite as many words as possible from the list, but this time, without their oral presentation before. The scores correspond each time to the number of

correctly repeated words. We used the following measures: (1) score trial 1 (Rey-1); (2) mean score trials 2–5 (Rey-2); (3) score delayed recall (Rey-3). Rey-1 represents principally verbal short-term memory (STM), Rey-2 verbal learning, and Rey-3 verbal long-term memory (LTM).

Fine and gross sensorimotor skills

We used the Purdue Pegboard (PP) test, administered according to the Lafayette manual (Lafayette, 1999), to evaluate manual fine and gross dexterity and bimanual coordination. The Pegboard contains 2 rows of 25 holes, oriented vertically. Two cups on top of the board contain pegs (diameter 1 mm), collars and washers. After a series of practice trials, the children inserted as many pegs as possible in the holes in 30 s, from top to bottom, using their right hand (PP-RH), then their left hand (PP-LH), and finally with both hands simultaneously (PP-BH). These tasks evaluate gross hand dexterity and bimanual coordination, respectively. Then the children performed an assembly task working with both hands, placing as many assemblies in the holes as possible within 1 min (PP-Ass). This subtask requires bimanual coordination in combination with fine finger dexterity. One assembly consisted of a peg, a collar, and two washers (four elements) to be placed into one hole in a specific order. Four scores were collected, corresponding to the number of pegs placed (PP-RH, PP-LH, PP-BH) and the number of correctly inserted elements placed (PP-Ass).

Missing data

We report a total of six missing entrees (69 children, 15 different measures). Common approaches like substituting missing data by the group mean, induces the risk of reducing statistical variability and study validity. In consequence, we imputed the missing values using

the regularized iterative principal component analysis (PCA) algorithm developed by Josse et al. (2009), as implemented in the R package missMDA.

Correlation matrix

The root of our analyses consists of a simple correlation matrix using Spearman's non-parametric *rho* on ranks. We opted for a rank-based coefficient, as some outliers were present in our measures (see boxplots of all variables in supplementary Figure 1). As this is an exploratory study, we report all correlations with a *p*-value < .05 (uncorrected).

Exploratory Factor Analysis

We chose an exploratory factor analysis given that our hypotheses express relationships between our test measures that may share common underlying processing elements of which the structure is unknown (Child, 2006).

In order to determine an optimal number of factors for the Exploratory Factor Analysis, we performed 1) a Principal Component Analysis (PCA) and 2) a Parallel Factor Analysis (PFA) (Desjardins, 2018; Horn, 1965). We performed a PCA on the whole data set, using the R package FactoMineR (http://www.R-project.org). Before performing the PCA all data were first centered (M = 0.0) and scaled to unit variance (SD = 1.0).

After determining the optimal number of factors based on the PCA and PFA results, we applied an exploratory factor analysis for that number of factors based on the Spearman correlations with imputed missing values (see section on Missing data). Afterwards, we applied a direct oblique rotation (oblimin method) to render the latent factors more interpretable. The Exploratory Factor Analysis and PFA were performed using the R package psych.

Results

Correlation matrix

Table 2 depicts the correlation matrix based on the Spearman rank correlation test. We will only report and interpret significant correlations between different types of tests and not between subtests of a same type of test (for instance CCTT-1 vs CCTT-2, Rey 1 vs Rey-2). Such correlations are obvious, often close to one, and non-informative, as it is predictable that tests that measure closely related abilities show strong correlation.

INSERT TABLE 2 ABOUT HERE

Correlations between cognitive and musical skills

AMMA-T correlated with DSF (*rho*=0.305; *p*<0.0107), AMMA-R correlated with DSB (*rho*=0.246; *p*<0.0418). No significant correlations occurred between the AMMA and CCTT-1 & -2 and D2 scores.

Correlations between different general cognitive skills

DSB correlated to MR (*rho*=0.298; *p*<0.0128) and also to Rey-1 (*rho*=0.316; *p*<0.0081).

D2 scores related to those of CCTT-2 (*rho*=0.466; *p*<0.0001), as well as to Rey-2 (*rho*=0.324; *p*<0.0066) and Rey-3 (*rho*=0.287; *p*<0.0166). CCTT-2 also correlated to Rey-2 (*rho*=0.246; *p*<0.0420).

MR correlated to Rey-2 (*rho*=0.296; *p*<0.0136) and Rey-3 (*rho*=0.393; *p*<0.0008), and as already stated above, to DSB (*rho*=0.298; *p*<0.0128).

Correlations between sensorimotor and musical skills

No links were found between the different scores of the Purdue Pegboard (PP) and both musical subscores from the AMMA.

Correlations between different sensorimotor and general cognitive skills

PP-RH correlated to the CCTT-1 test (*rho*=0.287; *p<0.017*) and to the CCTT-2 one (*rho*=0.288; *p<0.0163*). The PP-RH scores also correlated to Rey-1 (*rho*=0.320; *p<0.0074*) and Rey-3 (*rho*=0.238; *p<0.0488*).

PP-LH correlated to CCTT-2 (*rho*=0.322; *p<0.0069*) and to the D2 score (*rho*=0.388; *p<0.0016*). Then PP-LH correlated negatively to DSB (*rho*=-0.0288; *p<0.0163*).

The PP-Ass score correlated to MR (*rho*=0.373; *p<0.0016*) and to Rey-3 (*rho*=0.271; *p<0.0241*).

There were no relationships between AMMA-R and PP.

Multivariate analyses

Both PCA and PFA indicated an optimal number of four latent factors.

The PCA showed a clear minimum square error of prediction (MSEP) using *k*-fold cross validation (Josse & Husson, 2012) at four components, explaining together 59.2% of the variance in the data. The PFA also indicated four factors, as the eigenvalues of the 5th factor were larger for the random data than the ones obtained for the original data set.

In consequence, we applied an Exploratory Factor Analysis with four latent factors based on the Spearman correlations with imputed missing values (see the section on Missing Data). Ordinary least squares were used to find the minimum residual solutions. Afterwards a direct oblique rotation (oblimin method) was applied in order to make the latent factors more

interpretable. Oblique rotation allows correlations among factors, appropriate here as certain measures are supposed to show diverse relationships.

Latent factors resulting from the Exploratory Factorial Analysis

Table 3 provides the loadings of all tests for the four factors as well as the communalities and uniqueness. Figure 1 represents the loadings of all tests on all four factors graphically. We will only interpret loadings above 0.3.

INSERT TABLE 3 ABOUT HERE

INSERT FIGURE 1 ABOUT HERE

Factor 1: "Verbal memory"

With strong loadings for Rey-3 (0.824) & Rey-2 (0.729) scores and moderate loadings for MR (0.485) and Rey-1 scores (0.371), this factor involves verbal memory and learning, as well as matrix reasoning.

Factor 2: "Music processing, short-term and working memory"

This factor involves musical processing with moderate loadings for the melodic (0.455) and rhythmic (0.372) AMMA scores, as well as strong loadings for short-term (0.613) and working memory results (0.707).

Factor 3: "Manual dexterity"

This factor involves manual dexterity and bimanual coordination, with strong loadings on this factor for PP-BH (0.754), PP-Ass (0.630) and PP-BH (0.598). The left hand (PP-LH) only

loads at 0.211, thus standing apart from the other three Purdue Pegboard measures. CCTT1-1 scores also load moderately on this factor (0.319).

Factor 4: "Visual Processing speed and attention"

Strong loadings by CCTT-2 (0.703) and D2 scores (0.629) and moderate loadings by CCTT-1 scores (0.361) characterize this factor, which essentially involves visual processing speed and attention. The PP-LH score also saturates this factor (0.449).

Discussion

The main finding of this study is the relative idiosyncrasy of musical cognitive faculties versus higher order cognitive abilities in musically untrained children, as illustrated by their loadings on latent Factor 2: "Music processing, short-term and working memory". Relatively important loadings for Factor 2 only manifested for short-term (DSF) and working memory (DSB) and for the tonal (AMMA-T) and rhythm (AMMA-R) subscores of the "Advanced Measures of Music Audiation" (AMMA). Correlations between the AMMA scores and scores of cognition also only manifested for DSF and DSB. The latter observations partially confirm our first hypothesis (see last paragraph of the Introduction). No relationships between the AMMA scores and higher order cognitive abilities occurred. Finally, uniqueness was high for both musical subscores.

DSB apparently plays a role as a hub, also supporting other cognitive abilities. Correlations showed also with Matrix Reasoning (MR) and short-term verbal memory (Rey-1) and logically of DSF, as DSB and DSF are distinct but interdependent cognitive functions (Grégoire, 2009). Relatively high communalities for DSB support this assumption. This could explain that music practice gradually intertwines and strengthens the links between musical and cognitive skills in children.

Finally, correlations between sensorimotor performance, measured by the different subtests of the Purdue Pegboard test, and cognitive function, supporting our second hypothesis, were quite extended. They concerned visual processing speed (CCTT-1 & 2) and mental flexibility (CCTT-2), selective attention (D2), short term verbal memory and learning (Rey-1 and Rey-3) and matrix reasoning (MR). It seems that easily executed and automatized sensorimotor skills may allow increased neurobehavioral freedom and learning during more complex tasks (Crespo-Eguilaz et al., 2014).

Correlations

Correlations between musical and other skills

As predicted by hypothesis 1, short-term auditory memory (DSF) and working memory (DSB) serve the detection of melodic and rhythmic differences between pairs of melodies. DSF correlated to AMMA-T, so short-term auditory memory underpinned melodic processing, allowing to retain the order of the pitches in serial order. DSB. Auditory working memory was implied in rhythmic processing, possibly reflecting involvement of the phonological loop of Baddeley's model of working memory, used to go back and forth between the first and the second melody to compare the rhythm (Baddeley, 2003). These results are also supported by the Exploratory Factor Analysis, with positive loadings on Factor 2 for both AMMA scores and both auditory memory scores (DSF & DSB). These findings confirm earlier results of impact of working memory on music and language processing and error detection (Degé et al., 2015; James et al., 2015; Oechslin et al., 2013). We did not find any associations between visual attention, processing speed or mental flexibility, as expressed by CCTT and D2 performance, and performance on the musical tasks, infirming the second part of hypothesis 1. Note that the findings in the literature on the association between attention, processing speed, executive function, and musical capacities are often the fruit of musical training (J. Bugos &

Mostafa, 2011; Bugos et al., 2007; Moreno et al., 2011; Moreno & Farzan, 2015; Roden et al., 2014), whereas our participants were musically naïve.

Surprisingly, none of the Purdue Pegboard scores related to any of the musical scores, infirming hypothesis 3. Possibly, links between sensorimotor skills and music processing manifest only in people who practice music (Martins et al., 2018). We did not find any significant correlations between the AMMA scores and the Rey scores either. Reported relationships between verbal learning memory and musical processing skills also rather occurred in musically trained individuals (Chan et al., 1998; Roden et al., 2012).

Correlations between cognitive and sensorimotor skills

The most compelling observation was the correlation between the test of fine finger dexterity and bimanual coordination, the assembly test of the Purdue Pegboard (PP-Ass) and abstract reasoning, as measured by MR. Being able to perform complex sensorimotor skills automatically and easily, may increase neurobehavioral freedom (Crespo-Eguilaz et al., 2014). Children suffering from developmental coordination disorder who performed poorly on the Purdue Pegboard test, were also hampered for perceptual management of complex visuospatial information (Noten et al., 2014) required to well perform the MR test. PP-RH, PP-LH and PP-BH all related to the CCTT and D2 test, showing that manual dexterity relates positively to performing these tests on visual processing speed, mental flexibility and attention. As both the CCTT and D2 are performed by hand, it seems plausible to presume that, if the procedural part of the test does require little effort, more resources are available to be mentally flexible and for rapid application of rules. Finally, at first sight less plausible findings are the correlations between PP-Ass and PP-RH with long-term verbal memory (Rey-3) and short-term verbal recall (Rey-1). This observation might be explained however by the fact that being "dexterous",

liberates resources to focus on the outside word, resulting in enhanced capacity to retain vocabulary.

Correlations between different general cognitive skills

A series of obvious correlations occurred within the pool of cognitive skills tested here and need no extensive explanation. For instance, the association between the D2 scores and CCTT-2 scores that evaluate analogous skills, like visual processing speed and attention, rule compliance and mental flexibility. Then both D2 and CCTT-2 correlated to Rey-2, D2 also to Rey-3, supporting previously observed shared variance between verbal memory and executive function (Duff et al., 2005). Another evident association linked working memory (DSB) to matrix reasoning (MR), as disclosed previously (Little et a., 2014). Links between MR and Rey-2 and Rey-3 seem less intuitive, verbal memory does not seem an ingredient of abstract thinking. But especially children may rely on semantics to perform the MR task (Mathieu, Booth, & Prado, 2015). As could be expected also, scores of auditory working memory for numbers (DSB) and of short-term verbal memory (Rey-1) were strongly linked.

Exploratory Factor Analysis

Each of the latent factors resulting from the Exploratory Factor Analysis showed a clear fingerprint. Factor 1 was mainly saturated by the three verbal memory and learning measures (Rey-1-2-3) but most strongly by verbal learning (Rey-2-3) and less by short-term verbal memory (Rey-1). Interestingly MR also saturated this Factor, probably showing that the children depended on semantics to solve the matrix reasoning problems.

Factor 2 represents music processing and auditory short-term and working memory, confirming hypothesis 1 partially. Auditory short-term and working memory and music processing, as measured here by both subscores of the AMMA, thus share underlying processing elements

that rely strongly on auditory recall. As no higher-order cognition tests saturated this factor, these results suggest relative independency of musical cognitive faculties in non-musician children. The high uniqueness of both AMMA-R and AMMA-T supports this supposition.

At the other hand, the fact that auditory working memory also supports higher-order cognition (MR and Rey-1) suggests that musical practice might enhance the development of higher-order cognitive functioning indirectly.

Factor 3 represents sensorimotor hand and arm function as measured here by the Purdue Pegboard. CCTT-1, a simple visual processing speed task performed by hand, also relies on this latent factor. Because the CCTT-1 simply requires connecting digits in increasing order by hand on a paper sheet, this is a plausible observation.

Factor 4 embodies a latent factor representing visual processing speed and attention, grouping both CCTT and the D2 measures. Rather implausible seems the saturation by PP-LH on this factor. We suggest that visual processing speed and attention may enhance left hand function.

Limitations

The strongest limitation of this study is the relative restraint number of participants. A greater population would have been advantageous for multivariate analysis. This restriction is the consequence of a trade-off between the scope of the comprehensive behavioral testing battery and the number of children we could examine in a limited amount of time.

The adopted alpha threshold of .05 for correlations requires prudence concerning an interpretation of the results. However, the Explanatory Factor Analysis results supported the relatively weak correlational results.

Conclusion

This study allowed to gain insight in the relative interconnection of musicality and cognition in naturally developing non-musician children. It seems that, without intensive musical practice, this interconnection is limited to basic building blocks of cognition: auditory short-term and working memory. Links to higher-order cognition did not occur and may only manifest following protocolled music practice over longer periods of time.

A noteworthy secondary finding is the correlation of manual dexterity with higher-order cognition. Specifically, the link between bimanual coordination of fine finger dexterity, implied in the Purdue Assembly task, and abstract reasoning as measured here by the Matrices subtests of the WISC-IV, shows the importance of mastering procedural skills allowing to free resources for higher-order cognitive function.

Acknowledgements

Author Contributions

Conceived and designed the experiment: CJ SZ MK. Performed the experiments: LA DG. Analyzed the data: CJ EDL SZ. Wrote the paper: CJ MK SZ.

Funding

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Tables

Table 1

Types of tests, Measures, Acronyms and involved abilities of all items of the test battery.

Type of Test	Measure	Acronym	Involved ability
Cognitive Function			
Digit span	Digit Span Forward	DSF	Short-term Memory
	Digit Span Backward	DSB	Working Memory
Test of Attention	D2	D2	Selective visual attention
Children's Color Trails Test	Subtest 1	CCTT-1	Visual processing speed
	Subtest 2	CCTT-2	Visual processing speed & Mental flexibility
Matrix reasoning		MR	Fluid Intelligence/Abstract reasoning
Rey Auditory Verbal Learning Test	Recall	Rey-1	Verbal short-term memory (STM)
		Rey-2	Verbal learning
		Rey-3	Verbal long-term memory (LTM)
Procedural Skills			
Purdue Pegboard	Right Hand	PP-RH	Gross dexterity right hand
	Left Hand	PP-LH	Gross dexterity left hand
	Both Hands	P-BH	Bimanual coordination
	Assembly	PP-Ass	Bimanual coordination & fine finger dexterity
Musicality			
Advanced Measures of	Tonal	AMMA-T	Tonal discrimination
Music Audiation	Rhythmic	AMMA-R	Rhythmic discrimination

Table 2

Spearman rank correlations between all test measures. *Rho* and p-values are depicted for each test, separated by a forward slash (/) Significant correlations (p<.05) are highlighted in red font. * p<0.05; ** p<0.005; *** p<0.0005. For the acronyms of the tests, refer to Table 1.

|	AMMA-R	AMMA-T	CCTT-1	CCTT-2	D2	DSB	DSF	MR	PP-Ass	PP-BH	PP-LH	PP-RH	Rey-1	Rey-2	Rey-3
AMMA-R															
AMMA-T	0.331 / 0.0054*														
CCTT-1	0.116 / 0.3445	-0.023 / 0.8509													
CCTT-2	-0.057 / 0.642	0.157 / 0.1977	0.574 / 0.0000***												
D2	-0.16 / 0.1892	0.008 / 0.9487	0.191 / 0.1153	0.466 / 0.0001***											
DSB	0.246 / 0.0418*	0.202 / 0.0953	-0.038 / 0.7539	-0.033 / 0.7876	-0.052 / 0.6704										
DSF	0.137 / 0.2607	0.305 / 0.0107*	0.043 / 0.7236	0.069 / 0.5707	0.164 / 0.1775	0.398 / 0.0007**									
MR	0.169 / 0.1649	-0.071 / 0.5627	0.063 / 0.6053	-0.006 / 0.9614	0.069 / 0.5721	0.298 / 0.0128*	0.096 / 0.4324								
PP-Ass	0.163 / 0.1797	-0.002 / 0.9852	0.15 / 0.2178	0.030 / 0.8090	-0.074 / 0.545	0.136 / 0.2651	-0.081 / 0.507	0.373 / 0.0016**							
PP-BH	0.004 / 0.9712	0.098 / 0.4245	0.275 / 0.0223*	0.232 / 0.0550	0.150 / 0.2175	0.023 / 0.8501	0.095 / 0.4362	-0.1 / 0.4143	0.431 / 0.0002***						
PP-LH	-0.035 / 0.7755	0.095 / 0.4363	0.202 / 0.0963	0.322 / 0.0069*	0.388 / 0.0016**	-0.288 / 0.0163*	-0.123 / 0.3154	-0.168 / 0.1683	0.09 / 0.4639	0.323 / 0.0068*					
PP-RH	0.087 / 0.4751	0.146 / 0.2299	0.287 / 0.017*	0.288 / 0.0163*	0.177 / 0.1449	0.142 / 0.2442	-0.007 / 0.9568	0.013 / 0.9132	0.272 / 0.0235*	0.590 / 0.0000***	0.104 / 0.3954				
Rey-1	0.056 / 0.6492	0.043 / 0.7241	0.129 / 0.2906	0.089 / 0.4671	0.142 / 0.2454	0.316 / 0.0081*	0.019 / 0.8750	0.164 / 0.1780	0.225 / 0.0627	0.179 / 0.1400	-0.008 / 0.9451	0.320 / 0.0074*			
Rey-2	-0.099 / 0.4168	-0.105 / 0.3913	-0.013 / 0.9129	0.246 / 0.0420*	0.324 / 0.0066*	0.181 / 0.1370	0.117 / 0.3380	0.296 / 0.0136*	0.033 / 0.7907	-0.108 / 0.3788	0.019 / 0.8754	0.050 / 0.6858	0.295 / 0.0139*		
Rey-3	-0.042 / 0.7314	-0.083 / 0.5002	0.183 / 0.1333	0.211 / 0.0822	0.287 / 0.0166*	0.115 / 0.3474	-0.066 / 0.5922	0.393 / 0.0008**	0.271 / 0.0241*	0.030 / 0.8069	0.048 / 0.6927	0.238 / 0.0488*	0.394 / 0.0008**	0.628 / 0.0000***	

Table 3

Results of the Exploratory Factor Analysis. Loadings on the four latent factors, communalities and uniqueness are represented for each test measure.

| TEST	F1	F2	F3	F4	communalities	uniqueness
AMMA -R	-0.119	**0.372**	0.180	-0.124	0.192	0.808
AMMA-T	-0.270	**0.455**	0.099	0.181	0.278	0.722
CCTT-1	0.048	-0.002	**0.319**	**0.361**	0.273	0.727
CCTT-2	0.109	0.035	0.156	**0.703**	0.581	0.419
D2	0.253	-0.014	-0.047	**0.629**	0.484	0.516
DSB	0.157	**0.707**	0.063	-0.163	0.593	0.407
DSF	-0.105	**0.613**	-0.112	0.212	0.400	0.600
MR	**0.485**	0.195	0.076	-0.224	0.341	0.659
PP-Ass	0.241	-0.011	**0.630**	-0.279	0.499	0.501
PP-BH	-0.154	-0.002	**0.754**	0.191	0.639	0.361
PP-LH	-0.068	-0.246	0.211	**0.449**	0.334	0.666
PP-RH	0.064	0.097	**0.598**	0.169	0.446	0.554
Rey-1	**0.371**	0.168	0.259	-0.009	0.274	0.726
Rey-2	**0.729**	0.077	-0.210	0.197	0.619	0.381
Rey-3	**0.824**	-0.063	0.118	0.060	0.718	0.282

Figures

Figure 1

Results of the Exploratory Factor Analysis. Color bars represent loadings for all test measures (color coding for all tests in right panel) for the four latent Factors (F1-4).
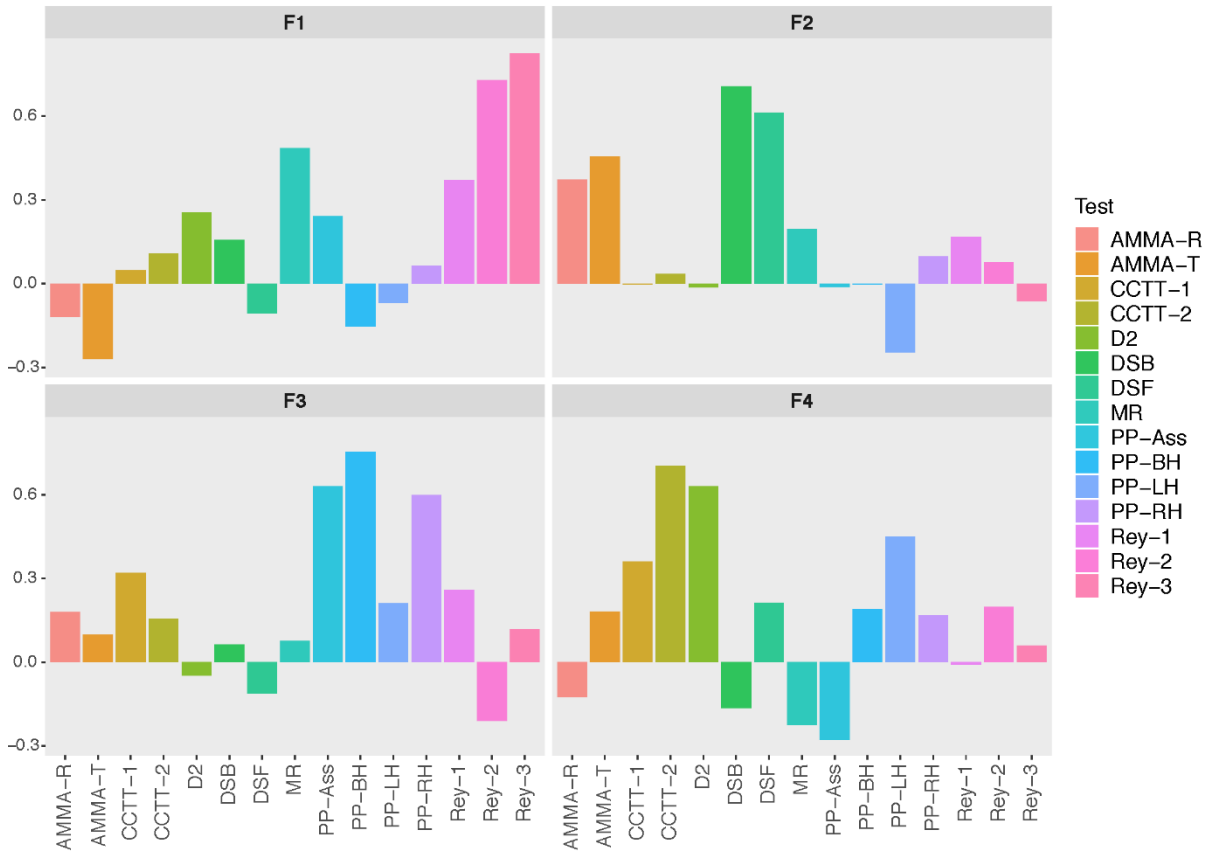
Supplementary Figure 1

Boxplots of all test scores. The boxes are arranged around the median. Dots represent outliers. For the acronyms of the tests, refer to Table 1.
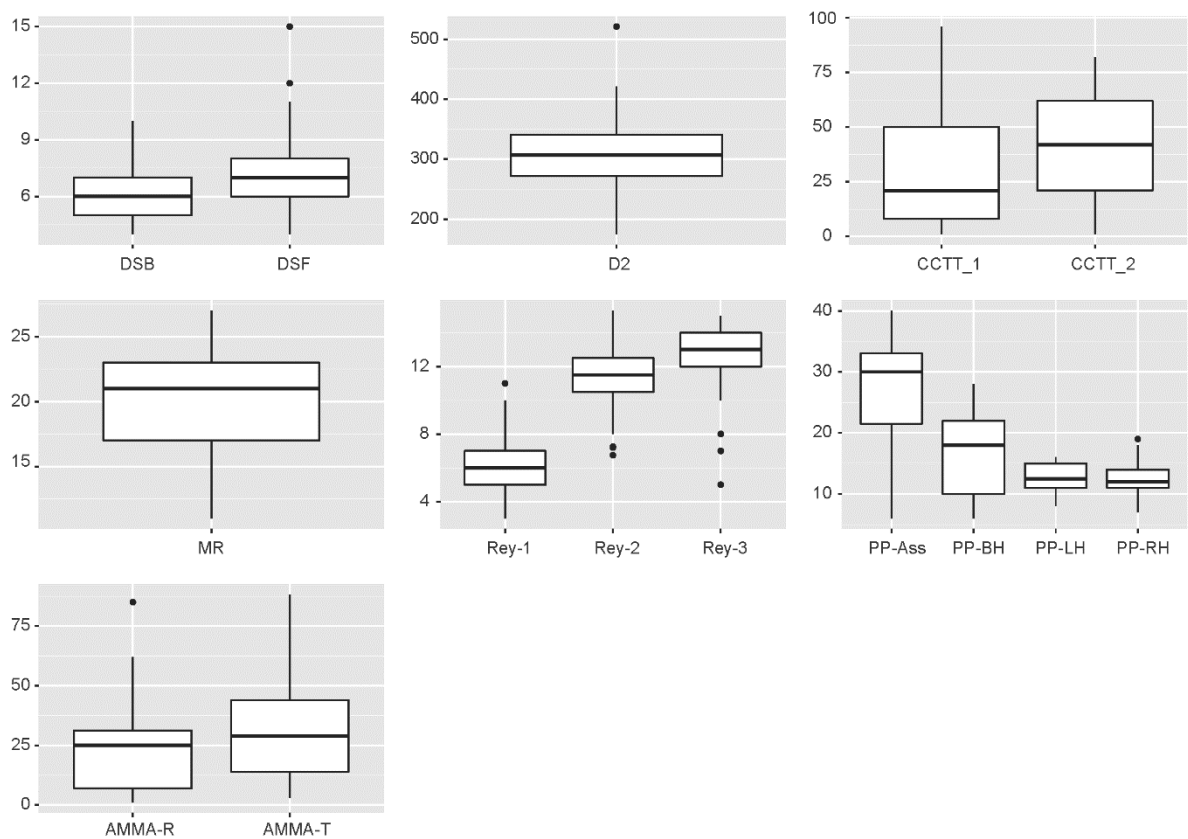
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