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Predicting Musical Aptitude and Achievement: Practice, Teaching, and Intelligence

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Abstract

Studies of expertise have traditionally had a strong focus on the role of one single factor, i.e. long-term deliberate practice, for expert performance. However, recent empirical and theoretical work strongly suggests that expertise is a function of many variables that may have practice-independent effects on performance, but also moderate the efficacy of practice itself. Here we study such interaction effects in a large cohort (N > 4,500) of Swedish twins, using music as a model domain, and measured expert performance (musical auditory discrimination) as well as self-reported real-life achievement as indices of expertise. Specifically, we test two recently proposed hypotheses, i.e. (1) that the efficacy of practice increases if the individual also takes part in teacher-led lessons, and (2) that practice efficacy increases with higher intelligence. The results did not support the first hypothesis. Both practice and frequency of music lessons had positive associations with the two measures of expertise but, contrary to predictions, the interaction between them was negative, i.e. the effect of each practiced hour decreased with more lessons. In contrast, the second hypothesis was supported by the data, i.e. we found a positive interaction between practice and intelligence, suggesting that higher cognitive ability is related to more efficient practice behaviors. Together the results further support that domain-specific expertise is a complex outcome, which depends on an interplay of a variety of factors.

Keywords

expertise, training, music, IQ, ability

Introduction

Deliberate practice theory, as proposed by Ericsson and colleagues (Ericsson, Krampe, & Tesch-Römer, 1993; Ericsson & Pool, 2016; Ericsson & Smith, 1991; Ericsson & Ward, 2007; Feltovich, Prietula, & Ericsson, 2006), has historically been one of the most influential theoretical frameworks in expertise research. A core element of this theory is that—with a few exceptions, such as body size, height, and the detrimental effects of disease and injury—expert performance is essentially a function of a single factor: the amount of deliberate practice an individual has accumulated (Ericsson, 2007; Ericsson et al., 1993; Ericsson & Pool, 2016).

Recent empirical work in the field challenges this view. Several meta-analyses show that, regardless of domain, deliberate practice explains only a low or modest proportion of the variance in expert performance (Hambrick et al., 2014; Macnamara, Hambrick,

& Oswald, 2014; Platz, Kopiez, Lehmann, & Wolf, 2014), the highest reported estimate to date being 36% for music in Platz et al. (2014). In other words, most of the variance in expert performance appears to be independent of deliberate practice. This non-practice-related variance is likely to reflect individual differences in psychological and physical traits relevant to performance. In musicians, for instance, working memory capacity predicts sight-reading over and above the effects of deliberate practice (Meinz & Hambrick, 2010), while other studies have found force control during piano strokes in pianists to be unrelated to musical training, but correlated with weight discrimination ability (Hosoda & Furuya, 2016). For chess, a recent meta-analysis found skill level to be related to general fluid intelligence and short-term/working memory (Burgoyne et al., 2016).

Furthermore, the efficacy of practice itself may be moderated by other factors. For example, Miksza has found that impulsivity is related to less well-structured practice behaviors in musicians (Miksza, 2006, 2011), while other researchers have found positive associations between music practice and openness to experience (Corrigall & Schellenberg, 2015; Corrigall, Schellenberg, & Misura, 2013; Swaminathan & Schellenberg, 2018). We have previously suggested (Ullén, Hambrick, & Mosing, 2016) that higher intelligence, which is related to sustained attention and metacognition (Schweizer & Moosbrugger, 2004; Schweizer, Moosbrugger, & Goldhammer, 2005; Stankov, 2000), may facilitate effective, goal-oriented practice strategies. Finally, recent work using genetically informative samples have confirmed that individual differences in expert performance and its acquisition are no exception to the general rule that human variation arises from an interplay between genetic and non-genetic factors (Hambrick, Macnamara, Campitelli, Ullén, & Mosing, 2016; Polderman et al., 2015; Ullén et al., 2016). Twin studies have thus demonstrated substantial genetic influences on practice (Hambrick & Tucker-Drob, 2015; Mosing, Madison, Pedersen, Kuja-Halkola, & Ullén, 2014), expert performance (Drayna, Manichaikul, de Lange, Snieder, & Spector, 2001; Mosing, Madison, et al., 2014; Mosing, Pedersen, Madison, & Ullén, 2014; Mosing, Verweij, Madison, & Ullén, 2016), correlations between practice and performance (Mosing, Madison, et al., 2014), and specialization within a domain of expertise (Mosing & Ullén, 2018).

Taken together, these findings strongly suggest that multifactorial models are needed to account for existing data and to generate new, fruitful, and testable hypotheses. Building on previous work (see e.g. Ackerman, 1996; Cattell, 1987; Gagné, 2013), we have recently proposed one such model, the Multifactorial Gene-environment Interaction Model (the MGIM; Ullén et al., 2016).

Multifactorial expertise models such as the MGIM are, of course, perfectly consistent with the common observation that long-term practice can result in impressive improvements of performance. However, another controversial claim of deliberate practice theory is that expertise acquisition crucially depends on a certain type of practice – that is, *deliberate practice* – while engaging in other types of domain-specific activities, such as those for extrinsic reward or pleasure, is considerably less effective (Boot & Ericsson, 2013; Ericsson et al., 1993). The relatively few studies that have directly compared the effects of deliberate practice and other domain-related activities on performance do not provide consistent support for this claim that deliberate practice is the primary predictor of performance. For instance, Howard (2012) found that number of played games predicted chess rating much more strongly than both time spent on practice and coaching. Similarly, Sonnentag and Kleine (2000) found that sales performance in insurance agents was better predicted by number of handled cases than by measures of deliberate practice.

Addressing this issue is complicated by the fact that the distinction between deliberate practice and other forms of practice often is unclear (Howard, 2009). Furthermore, in the expertise literature, authors have not always been consistent in their definitions of deliberate practice. Traditionally, deliberate practice has been defined as focused and effortful practice activities that are designed either by the performers themselves or by external agents such as teachers or coaches, and pursued with the explicit goal to improve performance (Ericsson et al., 1993; Keith & Ericsson, 2007). More recently, however, it has been suggested that deliberate practice by definition must involve a teacher or coach who is involved in designing practice activities, introducing the new term *purposeful practice* for practice activities that in previous studies were considered as deliberate practice but did not involve the participation of a teacher (Ericsson, 2016; Ericsson & Pool, 2016).

Disregarding these terminological confusions, the above discussion highlights an interesting general possibility, which is that the efficacy of practice activities is modulated by other factors, including both traits of the individual, such as intelligence, and environmental influences, such as regular interactions with a teacher. In line with this, Swaminathan and Schellenberg (2018) recently demonstrated that correlations between musical training and musical competence were evident only among participants scoring low on intelligence. If such moderating influences are present, they should be detectable as multiplicative interaction effects between practice and moderator variables on measures of performance and achievement. Here, we use music as model domain to investigate two specific hypotheses of this type that are directly suggested by the literature summarized above. Musical expertise involves adaptations in sensory, cognitive, and motor systems that allow for an effective processing of musical information, e.g. discrimination of musical sounds, score reading, and instrumental performance/singing (Deutsch, 2013).

First, we test whether teaching and practice both have additive (main) effects on real life musical achievement and music aptitude, two measures strongly associated with musical expertise (Ruthsatz, Detterman, Griscom, & Cirullo, 2008), and whether there is an interaction between practice and frequency of music lessons in the prediction of musical achievement, in line with Ericsson's recent claims that teacher-led deliberate practice is a stronger predictor of performance than is purposeful practice alone (Ericsson, 2016; Ericsson & Pool, 2016). Second, we test whether there is an interaction between practice and intelligence in the prediction of musical expertise, as would be suggested by the hypothesis by Ullén and coworkers (2016) that higher intelligence is related to more effective practice strategies.

Methods

Sample

Data for the present study were collected in 2012 and 2013 as part of a web survey administered to a cohort of young adult twins registered with the Swedish Twin Registry aged 27 and 54 (Lichtenstein et al., 2002; Lichtenstein et al., 2006). The web survey was designed to collect extensive information on music-related variables and the study was approved by the Regional Ethics Review Board in Stockholm (Dnr 2011/570-31/5). All 11,543 twins participating in the study gave informed consent before continuing with the survey. For further information on the data collection procedure and the web survey, see (Mosing, Madison, et al., 2014). Approximately 67% (N = 7,791) of the participants reported that they had played a musical instrument (including singing). Of those, an additional 67 individuals were removed from the analyses, including 18 individuals who reported that they had stopped playing before their reported start date, 44 individuals who reported zero practice hours, and five individuals who did not report their practice hours, leaving a final sample of 7,724 participants.

Measures

Music practice. As is standard in expertise research (Ericsson et al., 1993), the amount of music practice was determined on the basis of several retrospective self-report questions. Participants who reported that they had ever played an instrument or had actively sung were asked how many hours a week (in 10 categories ranging from 0, more than 6-9, to more than 40 hours) they had practiced during four age intervals (ages 0–5 years, 6–11 years, 12–17 years, and from 18 years until the date of measurement), taking into account what age they started (and stopped, when applicable) practicing. From these responses, a measure of overall music practice hours was calculated by computing a sum-score estimate of the total hours of lifetime music practice.

Music lessons. The approximate amount of music lessons an individual had received during their lifetime was assessed similarly to music practice and based on several questions. First, individuals were asked whether they ever received music lessons other than the typical obligatory music lessons in school. Next, participants were asked during which age-intervals they participated in music lessons (i.e., ages 0–5 years, 6–11 years, 12–17 years, and from 18 years until the date of measurement). Finally, participants were asked to indicate how often they participated in lessons during each of the age periods based on seven categories: once a year (1), one to 11 times a year (2), once or twice a month (3), every second week (4), weekly (5), twice a week (6), or more than three times a week (7). Based on the age that was indicated as start and (possibly) stop date, a sum score of lifetime total lessons was calculated by summing the years per period by frequency of lessons (category) in each period.

Musical achievement. An adapted and translated version of the Creative Achievement Questionnaire (CAQ; Carson, Peterson, & Higgins, 2005), a self-report inventory designed to assess involvement and achievement in different arts and science domains, was included in the questionnaire. Here, only the music item was used, which consisted of seven statements about music achievement: (1) “I am not engaged in music at all” (44.5%); (2) “I am self-taught and play music privately, but I have never played, sung or shown my music to others” (10%); (3) “I have taken lessons in music, but have never player or sung for others or shown my own music to others” (14%); (4) “I have played or sung, or my music has been played in public concerts in my home town, but I have not been paid for this” (22.9%); (5) “I have played or sung, or my music has been played in public concerts in my home town, and I have been paid for this” (7%); (6) “I am professionally active as a musician” (1.1%); (7) “I am professionally active as a musician and have been reviewed/featured in the national or international media and/or have received an award for my musical activities” (0.6%). As the sample size was very large, the variable was analyzed as a continuous variable, even though there were only seven categories and the distribution was positively skewed. However, analyses were replicated with a dichotomized musical achievement outcome score, i.e., grouping those who played in public (category 4 to 7) versus those who played only privately or where not engaged with music anymore (category 1 to 3) (see Analyses below).

Musical aptitude. This was measured with a music auditory discrimination task—the Swedish Musical Discrimination Test (SMDT)—which includes three subscales measuring pitch, melody, and rhythm discrimination (Ullén, Mosing, Holm, Eriksson, & Madison, 2014). The Pitch subtest participants consisted of 27 trials with two successive tones that differed in pitch. Participants had to indicate whether the second tone was lower or higher than the first. The Melody subtest consisted of 18 trials with two isochronous sequences of four to nine tones. In the second sequence, the pitch of one randomly selected tone was altered without altering the melodic contour of the first sequence. Participants were asked to indicate which tone in the second sequence differed from the first. Finally, the Rhythm subtest consisted of 18 trials of two rhythmical sequences of five to seven tones (with the same pitch) that were the same or different from each other, in which case one note was moved in time or a different starting point in the sequence was used. Participants had to indicate whether the two rhythmical sequences were the same or different. Internal consistencies and split-half reliabilities of the three subscales were high (ranging between 0.79 and 0.89). The three resulting sum-scores of the correct trials (Pitch, Melody, and Rhythm scores) were then standardized and then summed to derive an overall musical aptitude score for each participant who had valid scores on all subtests. For a detailed description and psychometric validation of the SMDT, see Ullén et al. (2014).

Intelligence. Psychometric intelligence (IQ) was measured with the Wiener Matrizen-Test (WMT; Formann & Piswanger, 1979), a visual matrix test of non-verbal ability similar in construction to and correlating highly with Raven's standard progressive matrices (r = 0.92) (Formann & Piswanger, 1979). The test consists of 24 multiple choice items; participants had the standard 25 minutes to complete the test. Correctly answered items are summed to yield the test score. The resulting IQ score was standardized. The WMT has been shown to have good reliability in both paper-and-pencil (Cronbach's alpha = 0.81) and online (Cronbach's alpha = 0.79) administrations (Formann & Piswanger, 1979; Ullén et al., 2012).

Education. Participants were asked about their highest level of education allowing for ten response options ranging from "*primary school unfinished (1)*," over *"high school finalized (4)*," and "*a finalized university degree (8)*," to *"PhD or doctorate (10)."* As most participants reported to have at least finalized high school or even a university degree, resulting in a non-normal distribution, the variable was dichotomized to *"no finalized university degree (0)"* and *"a university degree (or higher) (1)*," resulting in an about equal distribution.

Analyses

Linear regression analyses were conducted with musical achievement and musical aptitude, respectively, as continuous outcome variable and music practice, music lessons, IQ, and age as continuous predictors, and education and sex as dichotomous predictors. All variables (except for education, age, and sex) were converted to z-scores with a mean of zero and a standard deviation of one. Two models were fitted for each musical outcome measure, one with an interaction effect between music practice and lessons and a second one with an interaction effect between music practice and IQ in addition to the above-mentioned main effects. Robust estimators of standard errors for clustered data were used to account for relatedness in the sample (i.e. correlations within twin pairs).

The musical achievement outcome was somewhat skewed. Thus, as a sensitivity check to make sure the results were reliable, analyses were repeated with a dichotomized musical achievement outcome score (using logistic regression), i.e., grouping those who played in public versus those who played only privately, and the continuous untransformed predictors. All analyses were conducted in StataIC 14 (StataCorp, 2016).

Results

After removing individuals with missing data on any of the (co-)variables, the final sample consisted of 4,521 and 4,587 individuals for the aptitude and the achievement analyses, respectively. Of those about 63% were female, 57% had finalized a university degree, and the mean age was 41 years (SD = 8). Descriptive statistics and phenotypic correlations are shown in Table 1. The phenotypic correlation between musical lessons and practice was $r = 0.53$ ($p < 0.001$).

Table 1. Sample descriptives for raw scores of music practice, music lessons, IQ, and the two measures of musical expertise - music achievement and music aptitude – in the final sample.

	Musical achievement *N* = 4587				**Music aptitude *N* = 4521**			
Measures	Range	Mean	*SD*	*r*	Range	Mean	*SD*	*r*
Expertise	1-7	2.43	1.50	1.00	16-62*	41.53	7.51	1.00
Practice	52-23,920	3499.74	3808.27	0.61	52-23,920	3534.48	3821.52	0.30
Lesson	0-308	36.86	51.0 7	0.49	0-308	37.28	51.42	0.30
IQ	0-24	13.31	5.19	0.13	0-24	13.39	5.18	0.32

*The raw sum score for aptitude is shown here. For the final regression analyses, the score of each subscale was standardized first and then summed to a total standardized score as one scale had more items (see Methods).

Results of the main regression analyses with musical achievement as the dependent variable using standardized variables (z-scores except for education, age, and sex) are shown in Table 2. Both music practice and music lessons were significantly associated with musical achievement, with higher achievement with increased number of training hours. IQ also had a significant main effect on musical achievement. The practice × IQ interaction term was significant with a positive regression coefficient, indicating that the associations between practice hours and musical achievement become stronger with higher IQ. The practice × lesson interaction was also highly significant, albeit with a negative regression coefficient, indicating that the association between practice and achievement becomes weaker as the number of music lessons increases. Of the covariates, only age and sex were significant, with somewhat lower achievement for females relative to males and older participants relative to younger participants. The overall model explained 44% and 46% of the variance in musical achievement without and with the interaction terms, respectively.

Table 2. The phenotypic cross-sectional association between music practice, music lessons, IQ, and the two indicators of musical expertise adjusted for age, sex, and education. Note that all variables (except for education, age, and sex) have been converted to z-scores with a mean of zero and a standard deviation of one. Model 1 without any interaction terms and Model 2 including interactions term for practice by lesson and practice by IQ.

	Musical achievement		Musical aptitude	
	Model 1	Model 2	Model 1	Model 2
	Beta (95% CI)	Beta (95% CI)	Beta (95% CI)	Beta (95% CI)
Music Practice	0.529** (0.495, 0.563)	0.537** (0.502, 0.571)	0.162** (0.137, 0.187)	0.165** (0.140, 0.190)
Music Lesson	0.227** (0.198, 0.257)	0.381** (0.345, 0.416)	0.111** (0.087, 0.135)	0.168** (0.136, 0.199)
Practice×Lesson	--	-0.127** (-0.147, -0.107)	--	-0.047** (-0.063, -0.031)
IQ	0.067** (0.041, 0.092)	0.052** (0.027, 0.077)	0.210** (0.188, 0.232)	0.204** (0.182, 0.227)
Practice×IQ	--	0.082** (0.055; 0.109)	--	0.033* (0.010, 0.057)
Education	0.034 (-0.015, 0.084)	0.029 (-0.019, 0.078)	0.058* (0.016, 0.101)	0.057* (0.015, 0.099)
Age	-0.018** (-0.021, -0.015)	-0.017** (-0.020, -0.014)	-0.008** (-0.010, -0.005)	-0.007** (-0.010, -0.005)
Sex	-0.072* (-0.122, -0.022)	-0.087** (-0.136, -0.038)	-0.160** (-0.203, -0.117)	-0.166** (-0.209, -0.123)

*$p < 0.01$, **$p < 0.001$

When repeating the analyses with musical aptitude (a normally distributed variable) as the dependent variable, all significant results were replicated, with all main effects, including age and sex, as well as both interaction terms being significant and in the same direction, although effects sizes were somewhat smaller. Further, education had a significant main effect on musical aptitude, with higher education being associated with higher musical aptitude. The overall model explained 22% and 23% of the variance in musical aptitude without and with the interaction terms, respectively. Sensitivity analyses with the dichotomized musical achievement (see Supplementary Table 1) confirmed all results with the continuous musical achievement outcome, with the one exception that there was a weak negative main effect of IQ in the model including the interaction terms.

Discussion

In the present study, we investigated two hypotheses regarding the relationship between music practice, music lessons, and IQ on real life musical expertise. First, we tested whether teaching and practice have additive as well as positive multiplicative effects on musical achievement. Our results confirmed highly significant additive effects of both variables, which were independent of covariates and interaction terms included, as well as scoring of the outcome variables (i.e. a dichotomized or continuous musical achievement scale). However, contrary to the hypothesis stemming from the deliberate practice theory, we found a negative interaction effect. The same pattern of effects was found when using musical aptitude rather than achievement as outcome variable. Second, we tested whether musical ability is related to a positive interaction between practice and intelligence. This hypothesis was confirmed, with a significant positive interaction between IQ and practice being present throughout the investigated models.

Practice, Lessons, and Musical Outcomes

The finding of a positive main effect of practice on musical ability and achievement must be seen as unsurprising in light of the expertise literature. Many studies have emphasized the critical importance of long-term practice for the acquisition of expert performance (Ericsson, 2006; Ericsson et al., 1993), and recent meta-analyses confirm a positive association between cumulative measures of practice and performance in all expertise domains (Macnamara et al., 2014). In part, these associations may reflect causal influences of practice on performance and achievement. Indeed, the main effect of practice on musical achievement, which evidently requires extensive skill learning, was higher (0.53) than the main effect on musical aptitude (0.16). A large literature on skill learning suggests that modifiable processes activated by practice may result in improvement of performance through mechanisms such as automation (Hill & Schneider, 2006; Schneider & Shiffrin, 1977), adaptations in sensory and motor systems (Calvo-Merino, Glaser, Grezes, Passingham, & Haggard, 2005; Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995; Pantev & Herholz, 2011), chunking of information (Gobet, 2005; Guida, Gobet, Tardieu, & Nicolas, 2012), and domain-specific boosting of working memory (Gobet, 2016; Ullén, de Manzano, & Mosing, in press; Ullén et al., 2016).

However, recent analyses using twin modelling also emphasize that associations between practice and performance related outcomes in cross-sectional and observational longitudinal data may have complex shared underpinnings. For instance, in earlier analyses in the same cohort, we have found that the association between music practice and musical aptitude (auditory music discrimination) is essentially driven by genetic pleiotropy (Mosing, Madison, et al., 2014). It therefore appears likely that the main effect of practice on musical outcomes observed here reflects a combination of possibly causal effects of practice and other mechanisms, potentially including (reverse) causality, genetic pleiotropy and, importantly, gene-environment correlation (*r*GE). For example, it is quite likely that children who have musical talent are more likely to take up practice because (1) they simply show more interest in music and actively seek a musical environment (active *r*GE), or (2) their parents may recognize their talent and encourage their interest further by providing musically stimulating environments (reactive *r*GE), or (3) their parents also possess musical talent and interest and have created a musically stimulating environment for themselves to which the child is automatically exposed (passive *r*GE).

The positive effect of taking music lessons on musical achievement was also expected. However, as for practice, it appears likely that this association is driven not only by the beneficial effects of professional instruction and coaching on musical competence, but also by other variables that simultaneously influence musical achievement and an interest in taking music lessons for prolonged periods of time. In line with this speculation, Corrigall and Schellenberg (Corrigall & Schellenberg, 2015) found that the duration of musical training among children aged 7-9 years was predicted by personality traits of both the children themselves and their parents, suggesting that genetic predisposition (or other familial factors) influences the likelihood of engaging in music training. Specifically, in both the children and their parents a high level of the trait openness-to-experience, which is related to artistic interests, predicted taking music lessons in the children. In line with this, we have previously found openness-to-experience to be genetically correlated with musical training (Butković, Ullén, & Mosing, 2015).

Finally, contrary to expectations, we found that there was a *negative* interaction between practice and education in the prediction of musical achievement. According to recent suggestions from Ericsson, within the framework of his deliberate practice theory, active instruction from a teacher or coach is essential for the acquisition of optimal practice strategies (Ericsson, 2016; Ericsson & Pool, 2016). This would imply that the efficacy of each practice hours *increases* with more musical education, i.e., a positive interaction between practice and music lessons on achievement. The present results do not support this notion. One possible explanation for the negative interaction effect could be the following: There are different musical activities, including practicing, taking lessons, playing with others, performing at concerts, listening to other musicians, and many more, which are beneficial for musical development and achievement. In this context, taking a large number of music lessons could be an indicator that the individual is part of a generally-enriched musical environment, which includes many activities that are beneficial for the acquisition of musical skills. Since the effects of each hour of practice on skill is often larger in beginners than in experienced experts (e.g. Crossman, 1959; Schmidt & Lee, 2005), the observed negative interaction effect could possibly reflect diminishing returns of practice among more skilled individuals.

Lastly, in line with past literature there was a significant negative effect of increased age and being female on both measures of musical expertise. Past literature, as well as listings of eminent musicians based on expert votes, indicate that women are underrepresented in the musical domain particularly on higher levels (Cox, 1926; Parr, 2019; Parr, 2019; Simonton, 1984). Many factors have been suggested to contribute to this difference in outcome, including e.g. cultural factors, discrimination, higher female involvement in parenting, as well as mean sex differences in personality traits, abilities, and interests (Eysenck, 1995; Mawang, Kigen, & Mutweleli, 2018; Simonton, 1992). Similarly, it is well known that musical aptitude declines with older age due to age-related cognitive decline and reduced sensitivity of the hearing apparatus (e.g. Bones & Plack, 2015). The finding that achievement would be rated as lower in the older participants, after controlling for practice and lessons, is somewhat puzzling and may be due to a cohort effect, where, for example, easier media access may allow younger people to feel that they have accomplished more, or older participants are being more humble. Finally, education had a significant effect only on musical aptitude but not on musical achievement. This finding may be due to the fact that, as we have previously shown, musical aptitude is strongly (genetically) related to a variety of cognitive measures such as general IQ, and processing speed (Mosing, Pedersen, et al., 2014; Mosing et al., 2016), while musical achievement seemed to be less associated with IQ (as shown here).

The Practice × Intelligence Interaction

In line with our second hypothesis, in all the models we tested, we found a significant positive interaction effect between music practice and IQ on achievement. Note that the WMT is similar to Raven's standard progressive matrices, which has been shown to tap into fluid or general intelligence (Carpenter, Just, & Shell, 1990; Formann & Piswanger, 1979). This suggests that a main pathway for effects of intelligence on musical achievement is through moderating effects of practice. That higher intelligence may be related to more effective practice strategies was previously proposed by Ullén and coworkers (Ullén et al., 2016) and is in line with past research showing that intelligence is associated with learning (particularly in cognitively demanding tasks; Ackerman & Cianciolo, 2000; Jensen, 1998), educational achievement (Deary, Strand, Smith, & Fernandes, 2007; Krapohl et al., 2014), cognitively demanding occupations (Gottfredson, 2003), and performance at work (Schmidt & Hunter, 1998). Cognitive mechanisms such as meta-cognition, attention, and working memory are likely to be important for effective deliberate practice and learning (Ullén et al., 2016), and also show substantial correlations with intelligence (e.g. Schweizer & Moosbrugger, 2004; Schweizer et al., 2005; Stankov, 2000). Similarly, moderate correlations have been found between reaction time (Deary, Der, & Ford, 2001; Mosing et al., 2016), processing speed (Lee et al., 2012; Neubauer, Spinath, Riemann, Borkenau, & Angleitner, 2000), and sensory discrimination tasks (Mosing, Pedersen, et al., 2014; Rammsayer & Brandler, 2007; Troche & Rammsayer, 2009) and intelligence—again all capacities which are likely important for expertise in various domains, including music. In principle, a positive intelligence × practice interaction could contribute to a so-called *Matthew effect*, where high-achieving individuals benefit more from practice, resulting in a gradual widening of individual differences in performance with increased training. Such phenomena have previously been reported in several longitudinal studies of skill acquisition e.g. in reading and mathematics (e.g. Morgan, Farkas, & Wu, 2011; Otto & Kistner, 2017).

Notably, when using musical aptitude (musical sensory discrimination) rather than achievement as outcome, the main effect of intelligence remained significant with the interaction in the model. This could reflect specific genetic overlaps between intelligence and sensory discrimination ability (Mosing, Pedersen, et al., 2014; Rammsayer & Brandler, 2007; Troche & Rammsayer, 2009). In line with this, we have found genetic pleiotropy to be an important factor underlying correlations between intelligence and musical aptitude (Mosing, Pedersen, et al., 2014), as well as between intelligence and sensory and motor timing accuracy (Mosing et al., 2016).

Conclusion

In summary, the present study showed that both music lessons and practice hours had a significant main effect on musical achievement. Further, a significant negative interaction effect between practice and lessons suggested that the effect of lessons became less important with increased practice hours and vice versa. Finally, we found a significant positive interaction effect between practice hours and intelligence suggesting that the effect of each hour of practice on musical ability increased as a function of intelligence. These findings highlight the importance of multiplicative interactions between practice and other variables for the acquisition of expertise (Ullén et al., 2016). More generally, these findings underscore the importance of taking a multifactorial perspective to understanding individual differences in expertise. Future research is needed to test whether similar phenomena are seen in other areas of expertise and whether the findings may be reflected in measures of brain plasticity.

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Authors' Declarations

The authors declare that there are no personal or financial conflicts of interest regarding the research in this article.

The authors declare that they conducted the research reported in this article in accordance with the Ethical Principles of the Journal of Expertise.

The authors declare that they are not able to make the dataset publicly available but are able to provide it upon request.

References

Ackerman, P. L. (1996). A theory of adult intellectual development: Process, personality, interests, and knowledge. *Intelligence, 22*(2), 227-257. doi:https://doi.org/10.1016/S0160-2896(96)90016-1

Ackerman, P. L., & Cianciolo, A. T. (2000). Cognitive, perceptual-speed, and psychomotor determinants of individual differences during skill acquisition. *Journal of Experimental Psychology: Applied, 6*(4), 259-290. doi:10.1037/1076-898X.6.4.259

Bones, O., & Plack, C. J. (2015). Losing the music: aging affects the perception and subcortical neural representation of musical harmony. *The Journal of neuroscience: the official journal of the Society for Neuroscience, 35*(9), 4071-4080. doi:10.1523/JNEUROSCI.3214-14.2015

Boot, W., & Ericsson, K. A. (2013). Expertise. In J. D. Lee & A. Kirlik (Eds.), *The Oxford Handbook of Cognitive Engineering* (pp. 143-158). Oxford, UK: Oxford University Press.

Burgoyne, A. P., Sala, G., Gobet, F., Macnamara, B. N., Campitelli, G., & Hambrick, D. Z. (2016). The relationship between cognitive ability and chess skill: A comprehensive meta-analysis. *Intelligence, 59*, 72-83. doi:10.1016/j.intell.2016.08.002

Butković, A., Ullén, F., & Mosing, M. A. (2015). Personality and related traits as predictors of music practice: Underlying environmental and genetic influences. *Personality and Individual Differences, 74*, 133-138.

Calvo-Merino, B., Glaser, D. E., Grezes, J., Passingham, R. E., & Haggard, P. (2005). Action observation and acquired motor skills: An fMRI study with expert dancers. *Cerebral Cortex, 15*(8), 1243-1249. doi:10.1093/cercor/bhi007

Carpenter, P. A., Just, M. A., & Shell, P. (1990). What one intelligence test measures: A theoretical account of the processing in the Raven Progressive Matrices test. *Psychological Review, 97*(3), 404-431.

Carson, S., Peterson, J. B., & Higgins, D. M. (2005). Reliability, validity, and factor structure of the creative achievement questionnaire. *Creative Research Journal, 17*(1), 37-50.

Cattell, R. B. (1987). *Intelligence: Its structure, growth, and action*. Amsterdam: North Holland.

Corrigall, K. A., & Schellenberg, E. G. (2015). Predicting who takes music lessons: parent and child characteristics. *Frontiers in Psychology, 6*, 282. doi:10.3389/fpsyg.2015.00282

Corrigall, K. A., Schellenberg, E. G., & Misura, N. M. (2013). Music training, cognition, and personality. *Frontiers in Psychology, 4*(222). doi:10.3389/fpsyg.2013.00222

Cox, C. M. (1926). *Early mental traits of three hundred geniuses*. Stanford, CA: Stanford University Press.

Crossman, E. R. F. W. (1959). A theory of the acquisition of speed-skill. *Ergonomics, 2*(1-4), 153-166.

Deary, I. J., Der, G., & Ford, G. (2001). Reaction times and intelligence differences - a population-based cohort study. *Intelligence, 29*(5), 389-399.

Deary, I. J., Strand, S., Smith, P., & Fernandes, C. (2007). Intelligence and educational achievement. *Intelligence, 35*(1), 13-21. doi:https://doi.org/10.1016/j.intell.2006.02.001

Deutsch, D. (Ed.) (2013). *The psychology of music* (3rd Edition ed.). San Diego, CA, USA: Academic Press.

Drayna, D., Manichaikul, A., de Lange, M., Snieder, H., & Spector, T. (2001). Genetic correlates of musical pitch recognition in humans. *Science, 291*(5510), 1969-1972.

Elbert, T., Pantev, C., Wienbruch, C., Rockstroh, B., & Taub, E. (1995). Increased cortical representation of the fingers of the left hand in string players. *Science, 270*, 305-307.

Ericsson, K. A. (2006). The influence of experience and deliberate practice on the development of superior expert performance. In K. A. Ericsson, N. Charness, P. J. Feltovich, & R. R. Hoffman (Eds.), *The Cambridge Handbook of Expertise and Expert Performance* (pp. 683-704). New York, NY: Cambridge University Press.

Ericsson, K. A. (2007). Deliberate practice and the modifiability of body and mind: Toward a science of the structure and acquisition of expert and elite performance. *International Journal of Sports Psychology, 38*, 4-34.

Ericsson, K. A. (2016). Summing up hours of any type of practice versus identifying optimal practice activities: Commentary on Macnamara, Moreau, & Hambrick (2016). *Perspectives on Psychological Science, 11*(3), 351-354.

Ericsson, K. A., Krampe, R. T., & Tesch-Römer, C. (1993). The role of deliberate practice in the acquisition of expert performance. *Psychological Review, 100*(3), 363-406.

Ericsson, K. A., & Pool, R. (2016). *Peak. Secrets From the New Science of Expertise*. New York, NY: Houghton Mifflin Harcourt.

Ericsson, K. A., & Smith, J. (Eds.). (1991). *Toward a General Theory of Expertise: Prospects and*

Limits. New York, NY: Cambridge University Press.

Ericsson, K. A., & Ward, P. (2007). Capturing the naturally occurring superior performance of experts in the laboratory: Toward a science of expert and exceptional performance. *Curr Dir Psychological Science, 16*(6), 346-350.

Eysenck, H. (1995). *Genius. The natural history of creativity.* (Vol. 12). Cambridge: Cambridge University Press.

Feltovich, P. J., Prietula, M. J., & Ericsson, K. A. (2006). Studies of expertise from psychological perspectives. In K. A. Ericsson, N. Charness, P. J. Feltovich, & R. R. Hoffman (Eds.), *The Cambridge Handbook of Expertise and Expert Performance* (pp. 41-68). New York, NY: Cambridge University Press.

Formann, W., & Piswanger, J. (1979). *Wiener Matrizen Test [Vienna Matrices Test]*. Göttingen: Hogrefe Verlag.

Gagné, F. (2013). The DMGT: Changes within, beneath, and beyond. *Talent Development & Excellence, 5*(1), 5-19.

Gobet, F. (2005). Chunking models of expertise: Implications for education. *Applied Cognitive Psychology, 19*(2), 183-204.

Gobet, F. (2016). *Understanding Expertise: A Multi-disciplinary Approach*. London, UK: Palgrave.

Gottfredson, L. S. (2003). g, jobs and life. In H. Nyborg (Ed.), *The scientific study of general intelligence. Tribute to Arthur R. Jensen.* (pp. 293-342). Oxford, UK: Elsevier Science.

Guida, A., Gobet, F., Tardieu, H., & Nicolas, S. (2012). How chunks, long-term working memory and templates offer a cognitive explanation for neuroimaging data on expertise acquisition: A two-stage framework. *Brain and Cognition, 79*(3), 221-244. doi:10.1016/j.bandc.2012.01.010

Hambrick, D. Z., Macnamara, B. N., Campitelli, G., Ullén, F., & Mosing, M. A. (2016). A new look at expertise: Beyond the experts are born vs made debate. *Psychology of Learning and Motivation, vol 64*, 1-55.

Hambrick, D. Z., Oswald, F. L., Altmann, E. M., Meinz, E. J., Gobet, F., & Campitelli, G. (2014). Deliberate practice: Is that all it takes to become an expert? *Intelligence, 45*, 34-45.

Hambrick, D. Z., & Tucker-Drob, E. M. (2015). The genetics of music accomplishment: Evidence for gene-environment correlation and interaction. *Psychonomic Bulletin and Review, 22*(1), 112-120.

Hill, N. M., & Schneider, W. (2006). Brain changes in the development of expertise: Neuroanatomical and neurophysiological evidence about skill-based adaptations. In K. A. Ericsson, N. Charness, P. J. Feltovich, & R. R. Hoffman (Eds.), *The Cambridge Handbook of Expertise and Expert Performance* (pp. 653-682). Cambridge, UK: Cambridge University Press.

Hosoda, M., & Furuya, S. (2016). Shared somatosensory and motor functions in musicians. *Scientific Reports, 6*, 10. doi:10.1038/srep37632

Howard, R. W. (2009). Individual differences in expertise development over decades in a complex intellectual domain. *Memory and Cognition, 37*(2), 194-209.

Howard, R. W. (2012). Longitudinal effects of different types of practice on the development of chess expertise. *Applied Cognitive Psychology, 26*, 359-369.

Jensen, A. R. (1998). *The g factor*. Westport: Praeger Publishers.

Keith, N., & Ericsson, K. A. (2007). A deliberate practice account of typing proficiency in everyday typists. *Journal of Experimental Psychology Applied, 13*, 135-145.

Krapohl, E., Rimfeld, K., Shakeshaft, N. G., Trzaskowski, M., McMillan, A., Pingault, J.-B., . . . Plomin, R. (2014). The high heritability of educational achievement reflects many genetically influenced traits, not just intelligence. *Proceedings of the National Academy of Sciences, 111*(42), 15273-15278. doi:10.1073/pnas.1408777111

Lee, T., Mosing, M. A., Henry, J. D., Trollor, J. N., Lammel, A., Ames, D., . . . Sachdev, P. S. (2012). Genetic influences on five measures of processing speed and their covariation with general cognitive ability in the elderly: the older Australian twins study. *Behavior Genetics, 42*(1), 96-106.

Lichtenstein, P., De Faire, U., Floderus, B., Svartengren, M., Svedberg, P., & Pedersen, N. L. (2002). The Swedish Twin Registry: a unique resource for clinical, epidemiological and genetic studies. *Journal of Internal Medicine, 252*(3), 184-205.

Lichtenstein, P., Sullivan, P. F., Cnattingius, S., Gatz, M., Johansson, S., Carlstrom, E., . . . Pedersen, N. L. (2006). The Swedish Twin Registry in the third millennium: an update. *Twin Research and Human Genetics, 9*(6), 875-882. doi:10.1375/183242706779462444

Macnamara, B. N., Hambrick, D. Z., & Oswald, F. L. (2014). Deliberate practice and performance in music, games, sports, education, and professions: A meta-analysis. *Psychological Science, 25*(8),

1608-1618.
Mawang, L. L., Kigen, E. M., & Mutweleli, S. M. (2018). The relationship between musical self-concept and musical creativity among secondary school music students. *International Journal of Music Education, 37*(1), 78-90. doi:10.1177/0255761418798402
Meinz, E. J., & Hambrick, D. Z. (2010). Deliberate practice is necessary but not sufficient to explain individual differences in piano sight-reading skill: the role of working memory capacity. *Psychological Science, 21*(7), 914-919.
Miksza, P. (2006). Relationships among impulsiveness, locus of control, sex, and music practice. *Journal of Research in Music Education, 54*, 308-323.
Miksza, P. (2011). Relationships among achievement goal motivation, impulsivity, and the music practice of collegiate brass and woodwind players. *Psychology of Music, 39*(1), 50-67.
Morgan, P. L., Farkas, G., & Wu, Q. (2011). Kindergarten children's growth trajectories in reading and mathematics: Who falls increasingly behind? *Journal of Learning Disabilities, 44*(5), 472-488. doi:10.1177/0022219411414010
Mosing, M. A., Madison, G., Pedersen, N. L., Kuja-Halkola, R., & Ullén, F. (2014). Practice does not make perfect: No causal effect of music practice on music ability. *Psychological Science, 25*(9), 1795-1803.
Mosing, M. A., Pedersen, N. L., Madison, G., & Ullén, F. (2014). Genetic pleiotropy explains associations between musical auditory discrimination and intelligence *PLoS One, 9*(11). doi:10.1371/journal.pone.0113874
Mosing, M. A., & Ullén, F. (2018). Genetic influences on musical specialization: A twin study on choice of instrument and music genre. Ann NY Acad Sci. *Annals of the New York Academy of Sciences, 1423*(1), 427-434.
Mosing, M. A., Verweij, K. J. H., Madison, G., & Ullén, F. (2016). The genetic architecture of correlations between perceptual timing, motor timing, and intelligence. *Intelligence, 57*, 33-40. doi:https://doi.org/10.1016/j.intell.2016.04.002
Neubauer, A. C., Spinath, F. M., Riemann, R., Borkenau, P., & Angleitner, A. (2000). Genetic and environmental influences on two measures of speed of information processing and their relation to psychometric intelligence: evidence from the German observational study of adult twins. *Intelligence, 28*(4), 267-289.
Otto, B., & Kistner, S. (2017). Is there a Matthew effect in self-regulated learning and mathematical strategy application? - Assessing the effects of a training program with standardized learning diaries. *Learning and Individual Differences, 55*, 75-86. doi:10.1016/j.lindif.2017.03.005
Pantev, C., & Herholz, S. C. (2011). Plasticity of the human auditory cortex related to musical training. *Neuroscience and Biobehavioral Reviews, 35*(10), 2140-2145.
Parr, F. (2019, 22.07.2019). The 20 greatest pianists of all time. Retrieved from http://www.classical-music.com/article/20-greatest-pianists-all-time
Parr, F. (2019, 22.07.2019). The 20 greatest violinists of all time. Retrieved from http://www.classical-music.com/article/20-greatest-violinists-all-time
Platz, F., Kopiez, R., Lehmann, A. C., & Wolf, A. (2014). The influence of deliberate practice on musical achievement: a meta-analysis. *Frontiers in Psychology, 5*, 646.
Polderman, T. J. C., Benyamin, B., de Leeuw, C. A., Sullivan, P. F., van Bochoven, A., Visscher, P. M., & Posthuma, D. (2015). Meta-analysis of the heritability of human traits based on fifty years of twin studies. *Nature Genetics, 47*(7), 702-709. doi:10.1038/ng.3285
Rammsayer, T. H., & Brandler, S. (2007). Performance on temporal information processing as an index of general intelligence. *Intelligence, 35*(2), 123-139.
Ruthsatz, J., Detterman, D., Griscom, W. S., & Cirullo, B. A. (2008). Becoming an expert in the musical domain: It takes more than just practice. *Intelligence, 36*, 330-338.
Schmidt, F. L., & Hunter, J. E. (1998). The validity and utility of selection methods in personnel psychology: Practical and theoretical implications of 85 years of research findings. *Psychological Bulletin, 124*(2), 262-274. doi:10.1037/0033-2909.124.2.262
Schmidt, R. A., & Lee, T. D. (2005). *Motor control and learning*. Champaign: Human Kinetics.
Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information-processing. 1. Detection, search, and attention. *Psychological Review, 84*(1), 1-66.
Schweizer, K., & Moosbrugger, H. (2004). Attention and working memory as predictors of intelligence. *Intelligence, 32*(4), 329-347.
Schweizer, K., Moosbrugger, H., & Goldhammer, F. (2005). The structure of the relationship between attention and intelligence. *Intelligence, 33*, 589-611.
Simonton, D. K. (1984). *Genius, creativity and*

leadership - historiometric inquiries. Lincoln, NE: Harvard University Press.

Simonton, D. K. (1992). Emergence and realization of genius: The lives and works of 120 classical composers. *Journal of Personality and Social Psychology, 61*, 829-846.

Sonnentag, S., & Kleine, B. M. (2000). Deliberate practice at work: A study with insurance agents. *Journal of Occupational and Organizational Psychology, 73*, 87-102. doi:10.1348/096317900166895

Stankov, L. (2000). Complexity, metacognition, and fluid intellligence. *Intelligence*, *28*(2), 121-143.

StataCorp. (2016). Stata: Release 14.2. College Station, TX: StataCorp LP.

Swaminathan, S., & Schellenberg, E. G. (2018). Musical competence is predicted by music training, cognitive abilities, and personality. *Scientific Reports, 8*(1), 9223-9223. doi:10.1038/s41598-018-27571-2

Troche, S. J., & Rammsayer, T. H. (2009). Temporal and non-temporal sensory discrimination and their predictions of capacity- and speed-related aspects of psychometric intelligence. *Personality and Individual Differences, 47*(1), 52-57. doi:10.1016/j.paid.2009.02.001

Ullén, F., de Manzano, Ö., Almeida, R., Magnusson, P. K. E., Pedersen, N. L., Nakmura, J., . . . Madison, G. (2012). Proneness for psychological flow in everyday life: Associations with personality and intelligence. *Personality and Individual Differences, 52*, 167-172. doi:10.1016/j.paid.2011.10.003

Ullén, F., de Manzano, Ö., & Mosing, M. A. (in press). Neural mechanisms of expertise. In P. Ward, J. M. Schraagen, J. Gore, & E. Roth (Eds.), *The Oxford Handbook of Expertise: Research & Application*. Oxford, UK: Oxford University Press.

Ullén, F., Hambrick, D. Z., & Mosing, M. A. (2016). Rethinking expertise: a multi-factorial gene-environment interaction model of expert performance. *Psychological Bulleting*, *142*(4), 427-446. doi:10.1037/bul0000033

Ullén, F., Mosing, M. A., Holm, L., Eriksson, H., & Madison, G. (2014). Psychometric properties and heritability of a new online test for musicality, the Swedish Musical Discrimination Test. *Personality and Individual Differences, 63,* 87–93.

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Supplementary Material

Supplementary Table 1. The phenotypic cross-sectional association between music practice, music lessons, IQ (all three standardized), and the dichotomized musical achievement scale adjusted for age, sex, and education. Model 1 without any interaction terms and Model 2 including an interaction term for practice by lesson and practice by IQ.

	Binary musical achievement			
	Model 1		Model 2	
	Odds Ratio (95% CI)	*p*-value	Odds Ratio (95% CI)	*p*-value
Music Practice	3.076 (2.728; 3.469)	<0.001	3.101 (2.744; 3.504)	<0.001
Music Lesson	2.072 (1.825; 2.353)	<0.001	2.558 (2.225, 2.940)	<0.001
Practice × Lesson	--	--	0.761 (0.707, 0.819)	<0.001
IQ	1.179 (1.077; 1.290)	<0.001	1.107 (1.015, 1.207)	0.022
Practice × IQ	--	--	1.348 (1.216; 1.494)	<0.001
Education	1.210 (1.021; 1.434)	0.028	1.214 (1.022, 1.442)	0.027
Age	0.954 (0.944; 0.965)	<0.001	0.954 (0.943, 0.965)	<0.001
Sex	0.857 (0.725; 1.014)	0.072	0.834 (0.702, 0.990)	<0.038