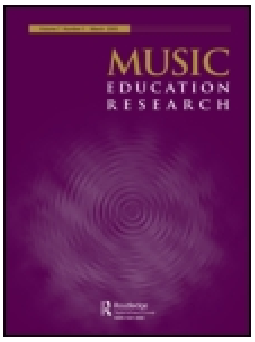

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Towards a dynamic model of skills involved in sight reading music

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This study investigates the relationship between selected predictors of achievement in playing unrehearsed music (sight reading) and the changing complexity of sight reading tasks. The question under investigation is, how different variables gain or lose significance as sight reading stimuli become more difficult. Fifty-two piano major graduates and undergraduates took part in an experiment which consisted of five different levels of sight reading complexity. Predictor variables were divided into three categories: (i) general cognitive skills (e.g. working memory capacity); (ii) elementary cognitive skills (e.g. reaction time); and (iii) expertise-related skills (e.g. accumulated sight reading or inner hearing). Regression analyses indicate that when sight reading stimuli is easy, general pianistic expertise is sufficient to be able to excel. However, with increasing task difficulty, psychomotor speed (as indicated by trilling speed), speed of information processing, inner hearing and sight reading expertise become more important. When sight reading complexity reaches its highest level, sight reading expertise still remains important, but psychomotor speed becomes the dominant predictor. Results indicate (i) that psychomotor speed and speed of information processing have a 'bottleneck' function and (ii) that there is a critical time window up to the age of 15 when sight reading expertise has to be acquired. It is concluded that with increasing task demands, sight reading ability is determined by both practice dependent skills and skills which are also assumed to be limited by innate abilities such as psychomotor movement speed. Thus we explain sight reading achievement as the result of specific combinations of different categories of skills which change with the demands of a task.

Introduction

The unrehearsed performance of music, so-called sight reading (SR), is a skill required by all musicians. It is characterized by great demands on the performer's capacity to process highly complex visual input (the score) under the constraints of real-time and without the opportunity of error correction. It is not only of particular interest for musical occupations such as piano accompanists, conductors or co-repetiteurs, but is also one of the five basic performance skills every musician should acquire (McPherson, 1995; McPherson *et al.*, 1997; McPherson & Gabrielsson, 2002). McPherson used path analysis to explore connections between them and a variety of other factors, such as early exposure, quality of study and

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enriching activities etc. He defines these skills as follows: to perform a repertoire of rehearsed music, to perform music from memory (where music is memorized using notation and re-created without the musical score), to play by ear (where music is both learned and reproduced aurally), to improvise in both 'stylistically conceived' and 'freely conceived' idioms, and to sight read music from notation that has not been previously seen or rehearsed.

However, up until now, differences between individuals in SR achievement have not been fully understood, and there has been no theory of SR that considers all relevant factors, such as expertise-related variables, speed of information processing or psychomotor movement speed. SR seems to be a complex skill that is based on visual pattern perception as well as on practice and speed of information processing (for a review of the current state of research, see Lehmann, 2005). From previous studies, we already know that there are a number of music-specific and non-music-specific skills that are relevant to the explanation of differences in SR performance. For example, the studies by Kornicke (1992, 1995), based on 73 piano students, revealed that SR expertise and aural imagery are the most influential factors. For example, the influential study by Lehmann and Ericsson (1996) demonstrated that the accumulated amount of time spent on activities related to accompanying and the size of accompanying repertoire are the best predictors for SR achievement. (For a detailed discussion of the relationship between the sub-skills of SR, see also Lehmann & McArthur, 2002.) Nevertheless, there has been no study that considers the influence of a wide range of predictors on musical achievement under the condition of changing task demands, and it remains open whether acquired expertise is the only predictor for SR achievement. For example, in a recent study, McPherson (2005) found evidence that SR achievement is not exclusively determined by accumulated hours of practice. He found that in 7–9-year-old instrumental beginners, practice could only account for 6–11% of difference in an SR test. The strongest predictor was the SR strategy used, which explained between 11% and 42% of variance. This means that as long as a sufficient number of additional predictors have not been considered, we cannot be sure about their influence.

Thus, as a first step we developed a general model of SR by determining the basic component skills involved. This model has been extended in a most recent study (Lee, 2004; Kopiez & Lee, in revision; Kopiez *et al.*, 2006) by also considering the influence of laterality on SR achievement as measured by handedness. Relevant skills considered were allocated to three groups: (i) general cognitive skills; (ii) elementary cognitive skills; and (iii) expertise-related skills (Table 2). For the group of general cognitive skills, our selection of music-specific and non-music-specific memory skills was derived from the typical demands of the task. From Sloboda's (1974) early studies, we know that the ability to read ahead while playing unrehearsed music is a condition for successful SR. However, without a sufficient short-term memory buffer, the advantage of an extended eye–hand span remains useless. Surprisingly, there are only a few studies that investigate the positive relationship between short-term memory and SR achievement (Eaton, 1978; Waters, Townsend & Underwood, 1998). Although SR is a typical task with high demands on working memory (this kind of memory is characterized by the simultaneous storage and processing of information), up until now this kind of memory has not been considered in SR research either. Therefore, music-specific as well as non-music-specific tests for short-term and working memory have been included in our study. Additionally, based on the findings by Salis (1978), we also included aspects of general mental capacity by use of a subsection of the Raven matrices (Raven, 2000). Salis found a correlation of $r = 0.57$ for the total IQ score (measured by the Wechsler Adult Intelligence Scales) and SR achievement, and a correlation of $r = 0.39$ for musical short-term memory (measured by the Drake Musical Aptitude Test) and SR.

For the group of elementary cognitive skills, selection of predictors was based on the assumption that under the time constraints of SR, the speed of information intake and of information processing plays a crucial role. For example, as Eaton (1978) could show, psychomotor skills (measured by the speed of key identification) are an important predictor of SR achievement. Thompson (1985) regarded SR as a transcription task, and he assumed that speed of information processing and reaction time play a crucial role. He included a musical reaction time task and found a correlation of $r = -.54$ between the number of correctly performed measures per second of the Watkins–Farnum Performance Scale and the time needed to perform a note suddenly appearing. Thus simple reaction time and psychomotor movement speed (wrist tapping and speed trilling) have been considered. Speed of information processing, which is also correlated with mental capacity, was also included and measured with a number combination test (NCT; Oswald & Roth, 1997).

For the group of expertise-related skills, we of course have to consider acquired SR and accompanying expertise. The importance of accumulated practice in the domain of SR has been explained in groundbreaking studies by Lehmann and Ericsson (1993, 1996). Auditory imagery has been considered because the study by Schleuter (1993) revealed some correlation between audiation and SR achievement ($r = 0.25$). Auditory imagery (also called audiation or inner hearing) is a construct developed by Gordon (1986, 1990, 1993) and means the ability to imagine the sound of musical notation independent from external sound sources such as an instrument. From the perspective of Gordon's 'music learning theory', this ability is related to musical talent. The importance of auditory imagery for SR music has been confirmed by Kornicke (1995) and Waters *et al*. (1998), who found that audiation is a good predictor. To summarize, the criterion for predictor selection was first based on relevance as reported in previous studies on SR, and secondly, on the availability of established methods of measurement. The underlying relationship between the selected independent variables is analysed by means of factor analysis and will be discussed in a forthcoming study (Kopiez & Lee, in revision).

As a result of our previous studies (Kopiez & Weihs, 2004; Lee, 2004; Kopiez *et al*., 2006; Kopiez & Lee, in revision), we proposed a general model of SR. Based on a set of 23 predictors, multiple regression analysis revealed that four predictors can explain up to 60% of variance of total SR achievement: psychomotor movement speed (as measured by trilling speed), SR expertise up to the age of 15, speed of information processing (so-called 'mental speed') and inner hearing. We argued that SR excellence is a complex combination of variables related to practice-related skills as well as to elementary cognitive skills. We also found evidence for the existence of a critical time window for the acquisition of SR expertise: the best expertise-related predictor was not the total of accumulated hours of SR practice but the amount acquired before turning 15. However, the question remains open, as to whether the influence of the revealed predictors varies with task demands or remains invariant over task levels. Thus in the present study we go one step further by dividing SR achievement into five different levels of complexity followed by regression analysis for each level.

Rationale for the study

Despite extensive research in expertise acquisition, individual differences that exist for SR achievement have not yet been fully explained. With the background of the brain's basic feature for optimum task adaptation, we assume that the weights of predictors for SR achievement, which have already been identified in a general model, change with the level of task difficulty. The main aim of this study, is therefore, to reveal the relationship between complexity of SR stimuli and predictor skills in order to build up a level-specific 'dynamic' model of SR as an addition to a general model.

Method

Subjects

Fifty-two piano majors, graduates and postgraduates from the Hanover University of Music and Drama served as subjects for this experiment. The mean age was 24.56 years (SD = 0.49 years); 24 males and 28 females took part. Subjects were paid for participation.

SR material and procedure

SR stimuli were selected from the University of South Africa exam syllabus for piano SR (UNISA, n.d.). The piece with the highest complexity was a piece that had been used for an SR competition at the Hanover University of Music and Drama. The advantage of using the UNISA material was that it had already been assessed and categorized into increasing levels of complexity. Pieces were of similar length and were arranged for solo voice and two-handed piano accompaniment by a professional composer (Figure 1). External judges (professional piano accompanists) evaluated the different levels of task complexity. Additionally, the complexity of pieces was scrutinized for physical surface complexity (Table 1). In total, two warm-up pieces were used for the subjects to become familiar with the laboratory situation and the test procedures, along with five pieces of increasing complexity.

For the construction of SR tasks, the ‘pre-recorded pacing melody paradigm’ (Lehmann & Ericsson, 1993, 1996) was used. The solo voice was performed by a violinist who recorded these melodies while synchronizing with a metronome through headphones. Subjects were given 60 seconds to study each piece without

Figure 1. Example for the sight reading task warm-up piece No. 1 anonymous. Piece was re-arranged for solo voice and accompaniment

Table 1. Physical surface complexity of the sight reading stimuli of each task level

Level	Left hand	Right hand	Both hands	No. of bars	Average no. of notes in one bar	Total duration (s)	Average time for one bar (s)
1	80	89	169	23	7.34	45	1.95
2	98	90	188	20	9.4	48	2.45
3	103	188	291	37	7.86	52	1.45
4	93	105	198	21	9.42	50	2.38
5	188	222	410	21	19.52	92	4.38

Rank order of task levels is based on expert ratings.

playing it. The cue to start playing was indicated by two full bars of clicks before the piece. Subjects listened to the solo track via loudspeaker, and a MIDI keyboard (with weighted hammers) was used to record the performances of subjects directly into a sequencing program.

Predictor variables: measurement of selected skills

The selected 23 independent variables were divided into three categories: (i) general cognitive skills; (ii) elementary cognitive skills; and (iii) practice-related skills. This section gives a short explanation for each predictor variable and the respective scoring method. Table 2 lists all 23 predictors and the scoring methods used.

General cognitive skills

Working memory. Subjects were required to add or subtract in steps of one to an increasing number of digits in a 3 × 3 matrix. The displayed matrix started off with only two cells being active but ended with seven active cells. Subtraction or addition was indicated by four up or down arrows appearing in a random order. An arrow pointing upwards meant plus one and an arrow pointing downwards meant minus one. Each calculation had to be performed on the current value of the cell, and the result had to be remembered. This task consisted of five warm-up and 18 test exercises. The percentage of correct answers was calculated with software developed by Oberauer *et al*. (2000) and used for data analysis.

Short-term memory test (STM). This numerical test consisted of a series of numbers, shown one at a time on a computer screen, which the subjects had to remember. Answers were typed in by the investigator and were shown on the screen with the option of correction if subjects felt that the answers were incorrect. Feedback was given as to how many of the numbers were remembered correctly. The test started with four digits per task and then increased by one digit every time until it reached nine digits per task. There were two warm-up and 18 test exercises. For scoring, the

Table 2. List of 23 grouped predictor variables and methods used for measurement

Skills group	Predictor variable (name used for data analysis)	Method of measurement
1. General cognitive skills	Short term memory capacity (STM)	Researcher developed software (mean% of correct items)
	Working memory capacity (WM)	Researcher developed software (mean% of correct items)
	Short term music specific memory (STMM)	Researcher developed software (no. of performed notes)
	General mental capacity (Raven D)	Series D of Raven's SPM (no. of correct items)
2. Elementary cognitive skills	Speed of information processing (NCT)	Number Combination Test (duration in seconds)
	Simple visual reaction time (RTV)	Researcher developed software (median in ms)
	Simple auditory reaction time (RTA)	Researcher developed software (median in ms)
	Tapping speed	Tapping device (median in ms of both hands)
	Trill speed* over 15 s, f.c.† 1–3, average of 2 trials	Keyboard trill (median in Hz)
	Trill speed* over 15 s, f.c.† 3–4, average of 2 trials	
3. Expertise related skills	Accumulated hours of solo practice up to the age of 10, 15, 18 and total (Solo 10, 15, 18, total)	Retrospective interview
	Accumulated hours of piano lessons up to the age of 10, 15, 18, and total (Lesson 10, 15, 18, total)	Retrospective interview
	Accumulated hours of sight reading expertise (SR) up to the age of 10, 15, 18, and total (SR 10, 15, 18, total)	Retrospective interview
	Inner hearing	Embedded melodies test (*d* prime)

*All trills were played with the right hand; †f.c., finger combination.

percentage of correct answers was used. Measurement was performed with software developed by Oberauer *et al*. (2000).

Short-term music-specific memory test (STMM). This task was an alternative to the numerical short-term memory test and tested music-dependent short-term memory. Tasks were derived from a study by Drösler (1989). Subjects had to look at a short melody of 12 bars for one minute and then try to play as many correct notes as they could from memory on a MIDI keyboard. Performance was recorded and the sum of all correct pitches performed by the subjects was used for data analysis.

Raven's D Matrix. To control for influences of general mental capacity, we used the Standard Progressive Matrices (Raven, 2000). Due to the limited time, only series D (12 items) was used. Scoring was based on the number of correct items.

Elementary cognitive skills

Number combination test (NCT). This is a pencil and paper test of perceptual and processing speed consisting of the numbers 1 to 90, which subjects had to join chronologically as fast as possible. The time taken to complete this test was measured by a stopwatch and used for data analysis. Test scores indicate speed of information processing (Oswald & Roth, 1997).

Auditory and visual reaction time (RTA and RTV). Simple reaction time using auditory and visual cues were used. Subjects had to release a Morse key as soon as they saw or heard the stimuli on the computer screen or from the computer loudspeaker. The time interval of stimulus appearance varied randomly between 500 and 2000 ms after a key was pressed by the subject. Data was recorded using software developed by the researchers and the median for each modality in ms was used for the data analysis. There were five warm-up and 20 test exercises for each modality.

Speed trilling. The music-specific psychomotor movement task consisted of speed trilling for 15 seconds. The two types of speed trills used were: the thumb and middle finger of the right hand on C4 and D4 (Trill 1–3); the middle finger and ring finger on E4 and E5 (Trill 3–4). Both trills were repeated once and the average of both medians in Hz was used for the data analysis.

Speed tapping. The non-music-specific psychomotor speed task was speed tapping (wrist tapping) for 30 seconds on a Morse key. Subjects were given a test trial and start hand was allocated randomly. Software developed by the researchers was used for evaluation and the median of the inter-tap interval for both hands in Hz was calculated.

Practice dependent skills

Inner hearing. To test for auditory imagery, the 'embedded melody paradigm' (Brodsky *et al*., 2003) was used (forced choice method). Pre-existing variations from piano literature were used by combining the original theme with a variation written by the composer or with a so-called 'lure melody' written by a composer of our department. The lure melody is similar to the theme but is distinctively different and has a significant deviation from the underlying melodic or harmonic structure of the melody. Thus for each example there were three versions: theme, variation and the lure melody. The variation of each theme was shown for 45 seconds using a PowerPoint presentation, and subjects had to imagine the sound without humming or singing the score. Presentation was followed (i) by the theme or (ii) by the lure melody through the speakers. Sound examples could be repeated. A forced-choice paradigm was used and subjects were required to decide whether the theme heard was embedded in the variation seen. The *d* prime value was then calculated (Macmillan & Creelman, 1991). After a pre-test, it was decided to use two warm-ups and five samples.

Retrospective interviews. According to the method used by Lehmann and Ericsson (1996), retrospective interviews, to elicit information about the number of accumulated hours of practice for solo and SR and the number of years of piano lessons starting from the beginning of instrumental lessons, were processed. Based on these interviews, the number of accumulated hours of practice up to the ages of 10, 15, 18 and total were calculated.

Results

Scoring of the SR performances

SR data was analysed using the researcher-developed software 'Midicompare' (Dixon, 2002), a software program that matches a subject's performance to the score with an adjustable window time. The software calculates the number of correct notes (matched score notes), missed notes and extra notes. In this study, however, only matched score notes (matches) are used for achievement analysis. We decided to use ± 0.25 seconds as the critical window time in order to have a cautious and conservative approach to performance evaluation. Table 3 shows the distribution of score matches for all five levels. This table confirms the correctness of our difficulty ratings and the selection of tasks, as the mean achievement decreases continuously from level 1 to 5 and corresponds to the increasing difficulty. Standard deviation increases with the difficulty level and indicates that the selected SR tasks produce a sufficient amount of variance. In the next step of data analysis, correlation and regression analyses will be processed to reveal the changing influence of predictors for each task level.

Table 3. Table of the scores of sight reading achievement from level 1 to level 5 and the total achievement scores for all 52 subjects

Levels	Min. (%)	Max. (%)	Mean (%)	SD (%)
1	50	100	87.95	14.23
2	28	96	80.38	16.66
3	21	99	72.12	22.96
4	8	99	49.42	27.63
5	8	95	39.50	23.10
Total average	27	97	61.55	17.34

Table 4. Correlation between level 1 of sight reading achievement and predictor variables

Rank	Predictor variables	*r*	*p*	*N*	r^2
1	SR 10	0.380**	0.003	52	14.44%
2	SR 15	0.361**	0.004	52	13.03%
3	NCT	−0.332**	0.008	52	11.02%
4	Speed trill 3–4	0.290*	0.019	52	8.41%
5	SR 18	0.269*	0.027	52	7.23%
6	SR total	0.236*	0.046	52	5.57%
7	Lessons total	0.234*	0.047	52	5.48%
8	Working memory	0.231*	0.050	52	5.37%
9	Inner hearing	0.205	0.073	52	4.20%
10	Speed trill 1–3	0.189	0.090	52	3.57%
11	Raven D	0.178	0.103	52	3.16%
12	Reaction time (visual)	−0.136	0.168	52	1.85%
13	Reaction time (auditory)	−0.131	0.178	52	1.85%
14	Solo 10	0.114	0.211	52	1.29%
15	Lessons 15	0.113	0.212	52	1.27%
16	Lessons 10	0.113	0.213	52	1.27%
17	Solo total	0.092	0.258	52	0.84%
18	Tapping speed	0.088	0.268	52	0.77%
19	STM music	0.079	0.289	52	0.62%
20	Lessons 18	0.070	0.311	52	0.49%
21	STM	0.044	0.378	52	0.19%
22	Solo 15	0.018	0.450	52	0.03%
23	Solo 18	0.002	0.493	52	0.01%

Abbreviations as in Table 2. Spearman rho (one-tailed); $^*p<0.05$, $^{**}p<0.01$.

Correlation analyses between SR achievement at each level and the 25 predictor variables

Correlations for level 1. In Table 4, results of the correlation analysis for level 1 are shown. It can be seen that accumulated hours of SR expertise up to the age of 10 and 15 (SR 10 and SR 15) have the two highest correlations with the achievement of the level 1 task. In third place of significant correlations, we find speed of information processing (NCT), followed by Trill 3–4, SR 18, SR total, total years of lessons and working memory capacity (WM). Correlations show a moderate strength and do not exceed 0.38. All three groups of skills (general, elementary, expertise-related skills) are represented and the eight significant predictor variables account for performance variance of between 5% and 14%.

Correlations for level 2. In Table 5, results of correlation analysis for level 2 are shown. Significant results for the first 10 ranks of correlation analysis show that psychomotor trilling speed (finger combination 3–4) has a high correlation ($r=0.51$) with level 2 of SR achievement. Speed of information processing increases its importance from the third rank in level 1 to the second rank in level 2. SR 10 and 15 remain important and Inner hearing ability and Trill 1–3 enter the group of

Table 5. Correlation between level 2 of sight reading achievement and predictor variables

Rank	Predictor variables	*r*	*p*	*N*	r^2
1	Speed trill 3–4	0.511**	0.000	52	26.11%
2	NCT	−0.484**	0.000	52	23.43%
3	SR 15	0.403**	0.002	52	16.24%
4	Inner hearing	0.390**	0.002	52	15.21%
5	SR 10	0.366**	0.002	52	13.40%
6	Speed trill 1–3	0.311*	0.012	52	9.67%
7	SR 18	0.288*	0.019	52	8.29%
8	STM	0.283*	0.021	52	8.01%
9	Working memory	0.273*	0.025	52	7.45%
10	SR total	0.245*	0.040	52	6.00%
11	Raven D	0.205	0.072	52	4.20%
12	Solo total	0.204	0.074	52	4.16%
13	Solo 15	0.183	0.097	52	3.35%
14	Solo 10	0.174	0.109	52	3.02%
15	Solo 18	0.163	0.124	52	2.66%
16	Lessons 18	0.163	0.124	52	2.66%
17	STM music	0.158	0.132	52	2.50%
18	Lessons total	0.103	0.233	52	1.06%
19	Tapping speed	0.063	0.330	52	0.04%
20	Reaction time (visual)	−0.048	0.366	52	0.02%
21	Reaction time (auditory)	0.030	0.417	52	0.09%
22	Lessons 10	0.025	0.431	52	0.00%
23	Lessons 15	0.024	0.433	52	0.00%

Abbreviations as in Table 2. Spearman rho (one-tailed); $^*p<0.05$, $^{**}p<0.01$.

significant predictors as new variables. Short-term memory capacity (STM) becomes significant and Working memory increases its importance. Correlations show a medium to strong tendency and increase up to 0.51. Again, all three groups of skills are represented by the 10 significant predictor skills, which account for performance variance of between 6% and 26%.

Correlations for level 3. In Table 6, correlation analysis shows only a few changes in predictor ranking: psychomotor speed (Trill 3–4 and 1–3) remain important as well as speed of information processing (NCT) and SR expertise (SR 15). As a new variable, tapping speed becomes significant ($r=0.27$), emphasizing the importance of psychomotor speed for SR. Correlations show a further increase and the first rank slightly improves to $r=0.52$ for Trill 3–4. All three groups of skills are represented again by the 11 significant predictor skills, which account for performance variance of between 7% and 27%.

Correlations for level 4. In Table 7, correlation analysis shows that speed of information processing (NCT) and inner hearing have the highest correlations ($r=-0.51$ and $r=0.47$). Trilling speed remains important for both finger

Table 6. Correlation between level 3 of sight reading achievement and predictor variables

Rank	Predictor variables	r	p	N	r^2
1	Speed trill 3–4	0.523**	0.000	52	27.35%
2	Speed trill 1–3	0.422**	0.001	52	17.81%
3	NCT	−0.390**	0.002	52	15.21%
4	SR 15	0.364**	0.004	52	13.25%
5	Inner hearing	0.350**	0.006	52	12.25%
6	Working memory	0.322**	0.010	52	10.37%
7	SR 10	0.307*	0.013	52	9.42%
8	STM	0.296*	0.016	52	8.76%
9	Speed tapping	0.274*	0.025	52	7.51%
10	SR 18	0.269*	0.027	52	7.24%
11	SR total	0.267*	0.028	52	7.13%
12	Solo 10	0.197	0.081	52	3.88%
13	Solo 15	0.189	0.090	52	3.57%
14	STM music	0.184	0.096	52	3.38%
15	Solo 18	0.166	0.119	52	2.75%
16	Solo total	0.166	0.120	52	2.75%
17	Lessons 15	0.127	0.186	52	1.61%
18	Lessons 10	0.126	0.186	52	1.58%
19	Raven D	0.126	0.186	52	1.58%
20	Lessons total	0.115	0.209	52	1.32%
21	Lessons 18	0.112	0.215	52	1.25%
22	Reaction time (visual)	−0.069	0.314	52	0.04%
23	Reaction time (auditory)	−0.044	0.378	52	0.02%

Abbreviations as in Table 2. Spearman rho (one-tailed); $^*p < 0.05$, $^{**}p < 0.01$.

combinations, however, some predictors loose significance: WM, SR 10, STM, tapping speed, SR 18 and SR total are no longer significant. As a new predictor from the group of general cognitive skills, the number of correctly solved items from the Raven matrices appears on rank 6, explaining 9% of variance. From the group of variables related to SR expertise, only SR 15 remains significant. The most surprising result is the salience of speed of information processing, which becomes more important than SR expertise at this high level of task difficulty. All three groups of skills are represented by the 10 significant predictor skills, which account for performance variance of between 9% and 26%.

Correlations for level 5. In Table 8 of correlation analysis, some new predictors become significant: SR 18, Solo 10 and 15, SR 10 and STM music enter the significant ranks. Compared with level 4, Raven D results no longer play a role. We have to bear in mind two findings from this table for later discussion: firstly, when SR reaches a highly challenging level, general pianistic expertise (solo practice) acquired early also becomes important; secondly, SR expertise has to be acquired before a certain age. It is not the total acquired number of hours that becomes significant but the amount of practice acquired up to the age of 15 ($r = 0.50$). At this level, general cognitive skills no longer play a role and only two of the three groups of skills are

Table 7. Correlation between level 4 of sight reading achievement and predictor variables

Rank	Predictor variables	*r*	*p*	*N*	r^2
1	NCT	−0.512**	0.000	52	26.21%
2	Inner hearing	0.474**	0.000	52	22.47%
3	Speed trill 3–4	0.413**	0.001	52	17.06%
4	SR 15	0.366**	0.004	52	13.39%
5	Speed trill 1–3	0.307*	0.013	52	9.42%
6	Raven D	0.306*	0.014	52	9.36%
7	Working memory	0.258	0.032	52	6.66%
8	SR 10	0.257	0.053	52	6.60%
9	SR total	0.219	0.059	52	4.79%
10	SR 18	0.214	0.064	52	4.58%
11	Tapping speed	0.191	0.087	52	3.65%
12	Reaction time (visual)	−0.182	0.098	52	3.31%
13	Solo total	0.154	0.137	52	2.37%
14	Solo 10	0.117	0.204	52	1.37%
15	Lessons total	0.111	0.217	52	1.37%
16	STM	0.082	0.282	52	0.67%
17	Lessons 10	0.065	0.325	52	0.42%
18	Lessons 15	0.064	0.327	52	0.41%
19	Lesson 18	0.063	0.328	52	0.39%
20	Reaction time (auditory)	−0.042	0.384	52	0.17%
21	STM music	0.029	0.420	52	0.08%
22	Solo 15	0.003	0.492	52	0.00%
23	Solo 18	0.003	0.493	52	0.00%

Abbreviations as in Table 2. Spearman rho (one-tailed); $p < 0.05$, $^{**}p < 0.01$.

represented by the ten significant predictor skills, which account for performance variance of between 6% and 25%.

Changes of predictor weights from level 1 to 5

To summarize the previous findings, the changing ranks of skills correlated with SR achievement are listed in Table 9. The visualization of this table, taking into account the significant and constantly present ranks of predictors over all five levels, is shown in Figure 2 (all eight variables shown in Figure 2 were found to be significant and were included in the top ten ranks from correlation analysis results, with the exception of WM at level 5). Both representations of the findings give a clear picture of the complex relationship between SR achievement and selected sub-skills. One remarkable finding is that there is not a single predictor that increases or decreases constantly in its impact over all five levels of task difficulty. The general development of changing importance can be seen when comparing correlations at level 1 to levels of higher difficulty. For example, the field of sub-skills at level 1 has an undifferentiated relationship to SR achievement with only moderate correlations of less than $r = 0.38$. With increasing task complexity, the relationship between

Table 8. Correlation between level 5 of sight reading achievement and predictor variables

Rank	Predictor variables	*r*	*p*	*N*	r^2
1	SR 15	0.502**	0.000	52	25.20%
2	Speed trill 1–3	0.424**	0.001	52	17.98%
3	Speed trill 3–4	0.417**	0.001	52	17.39%
4	SR 18	0.412**	0.001	52	16.97%
5	Solo 10	0.396**	0.002	52	15.68%
6	SR 10	0.395**	0.002	52	15.60%
7	Inner hearing	0.344**	0.006	52	11.83%
8	Solo 15	0.321*	0.010	52	10.30%
9	NCT	−0.269*	0.027	52	7.24%
10	STM music	0.256*	0.033	52	6.55%
11	Lessons 10	0.217	0.061	52	4.71%
12	Lessons 15	0.216	0.062	52	4.66%
13	Solo 18	0.214	0.063	52	4.58%
14	SR total	0.181	0.099	52	3.27%
15	Reaction time (visual)	−0.179	0.102	52	3.20%
16	Solo total	0.161	0.127	52	2.59%
17	Lessons 18	0.087	0.271	52	0.75%
18	Raven D	−0.083	0.278	52	0.69%
19	Working memory	0.081	0.285	52	0.65%
20	Lessons total	−0.057	0.343	52	0.32%
21	Speed tapping	0.049	0.366	52	0.24%
22	STM	0.047	0.371	52	0.22%
23	Reaction time (auditory)	0.032	0.411	52	0.10%

Abbreviations as in Table 2. Spearman rho (one-tailed); *$p < 0.05$, **$p < 0.01$.

predictors becomes more differentiated with a focus on SR expertise, speed of information processing, psychomotor speed and inner hearing.

Multiple regression analyses for SR achievement at each level and the 23 predictor variables

In order to consider the inter-dependencies of predictors derived from correlation analysis, all 23 predictor variables were used in the last step for multiple regression analysis of SR achievement. The method was 'stepwise'; the criterion for entering a new variable was $p < 0.05$ and for removal $p > 0.10$.

Multiple regression analysis of level 1. Analysis resulted in one regression model which consisted of only SR 10. This predictor alone can explain 6.6% of level 1 SR achievement. With the background of correlation analysis of this level (Table 4), this weak predictive quality of the regression model is due to a moderate correlation of all relevant predictors found for level 1. As can be seen in Table 4, no single predictor exceeded a correlation of $r = 0.38$.

Multiple regression analysis of level 2. Regression analysis for level 2 can explain 25.1% of variance (Table 11) with a model comprised of one variable related to

Table 9. The rank order of the predictor variables for levels 1 to 5 of sight reading difficulty

Rank	Level 1	Level 2	Level 3	Level 4	Level 5
1	SR 10**	Speed trill 3–4**	Speed trill 3–4**	NCT**	SR 15**
2	SR 15**	NCT**	Speed trill 13**	Inner hearing**	Speed trill 1–3**
3	NCT**	SR 15**	NCT**	Speed trill 3–4**	Speed trill 3–4**
4	Speed trill 3–4*	Inner hearing**	SR 15**	S.R 15**	SR 18**
5	SR 18*	SR 10**	Inner hearing**	Speed trill 1–3*	Solo 10**
6	SR total*	Speed trill 1–3*	WM**	Raven D*	SR 10**
7	Lessons total*	SR 18*	SR 10*	WM	Inner hearing**
8	WM*	STM*	STM*	SR 10	Solo 15*
9	Inner hearing	WM*	Tapping speed*	SR total	NCT*
10	Speed trill 13	SR total*	SR 18*	SR 18	STM music*
11	Raven D	Raven D	SR total*	Tapping speed	Lesson 10
12	RT (visual)	Solo total	Solo 10	RT (visual)	Lesson 15
13	RT (auditory)	Solo 15	Solo 15*	Solo total	Solo 18
14	Solo 10	Solo 10	STM music	Solo 10	SR total
15	Lessons 15	Solo 18	Solo 18	Lessons total	RT (visual)
16	Lessons 10	Lessons 18	Solo total	STM	Solo total
17	Solo total	STM music	Lessons 15	Lessons 10	Lessons 18
18	Tapping speed	Lessons total	Lesson 10	Lessons 15	Raven D
19	STM music	Tapping speed	Raven D	Lessons 18	WM
20	Lessons 18	RT (visual)	Lessons total	RT (auditory)	Lessons total
21	STM	RT (auditory)	Lessons 18	STM music	Tapping speed
22	Solo 15	Lessons 10	RT (visual)	Solo 15	STM
23	Solo 18	Lessons 15	RT (visual)	Solo 18	RT (auditory)

Abbreviations as in Table 2. Asterisk flags indicate correlations between predictors and sight reading achievement (Spearman rho, one–tailed; *$p < 0.05$, **$p < 0.01$).

psychomotor speed (Trill 3–4). Due to increasing task demands, we can observe that beginning at this level, psychomotor speed becomes increasingly important.

Multiple regression analysis of level 3. Results of the analysis (Table 12) show that the predictor for level 2 is also included in level 3. However, the difference is the percentage of variance that these models can account for. Compared with the model of level 2, based on the predictor's psychomotor speed, working memory and SR total, the best model for level 3 can explain 35.0% of variance.

Multiple regression analysis of level 4. At level 4 we can see that the structure of the regression model (Table 13) begins to differ in comparison to the models for levels 1–3. Inner hearing enters the analysis as the first predictor, followed by SR 15. Further improvement of the model's fit is reached in model 3, which includes speed of information processing (NCT) as a new variable (the negative beta coefficient for this predictor means that a shorter time for the NCT results in a higher achievement in SR), and finally, model 4 reaches 45.7% by adding SR 18 as a new predictor.

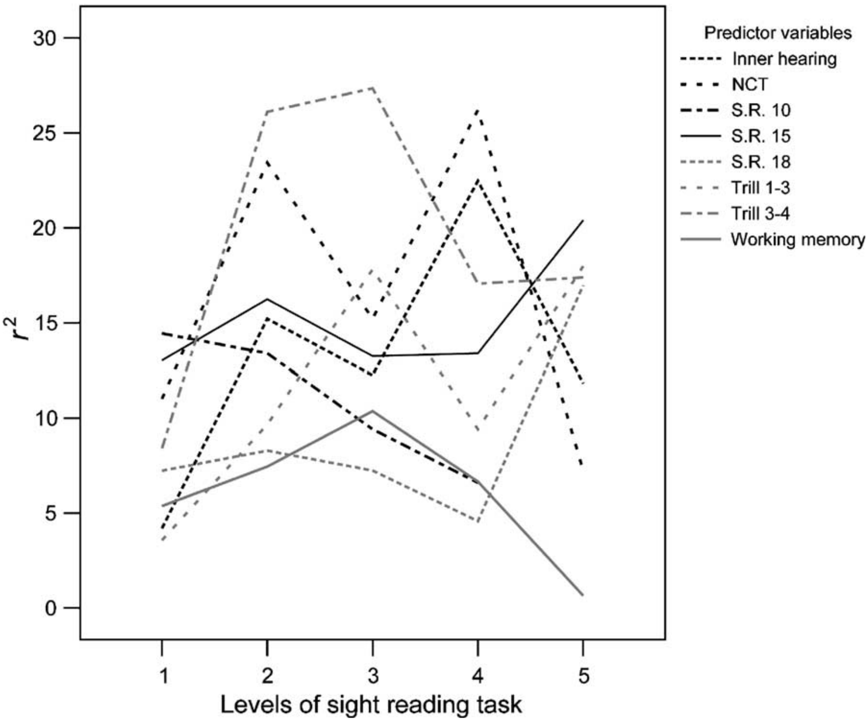

Figure 2. The changing weights r^2 of the first eight significant predictor ranks for levels 15 of sight reading achievement

Table 10. Regression analysis showing the influence of predictors for level 1 of sight reading achievement

Model	Variables	R^2 adjusted	ΔR^2	Standard beta coefficient	*p*
1	SR 10	0.066		0.290	0.037

Abbreviations as in Table 2.

Table 11. Regression analysis showing the influence of predictors for level 2 of sight reading achievement

Model	Variables	R^2 adjusted	ΔR^2	Standard beta coefficient	*p*
1	Speed trill 3–4	0.251		0.520	0.000

Table 12. Regression analysis showing the influence of predictors for level 3 of sight reading achievement

Model	Variables	R^2 adjusted	ΔR^2	Standard beta coefficient	*p*
1	Speed trill 3–4	0.232		0.496	0.000
2	Speed trill 3–4	0.317	0.080	0.507	0.000
	WM			0.306	0.011
3	Speed trill 3–4	0.350	0.040	0.502	0.000
	WM			0.277	0.018
	SR total			0.233	0.045

Abbreviations as in Table 2.

Table 13. Regression analysis showing the influence of predictors for level 4 of sight reading achievement

Model	Variables	R^2 adjusted	ΔR^2	Standard beta coefficient	*p*
1	Inner hearing	0.171		0.432	0.001
2	Inner hearing	0.309	0.138	0.395	0.001
	SR 15			0.388	0.002
3	Inner hearing	0.389	0.080	0.318	0.007
	SR 15			0.365	0.002
	NCT			−00.309	0.009
4	Inner hearing	0.457	0.068	0.259	0.022
	SR 15			10.102	0.001
	NCT			−00.330	0.003
	SR 18			0.785	0.011

Abbreviations as in Table 2.

Table 14. Regression analysis showing the influence of predictors for level 5 of sight reading achievement

Model	Variables	R^2 adjusted	ΔR^2	Standard beta coefficient	*p*
1	Speed trill 3–4	0.198		0.463	0.001
2	Speed trill 3–4	0.325	0.127	0.411	0.001
	SR 15			0.389	0.001
3	Speed trill 3–4	0.375	0.050	0.257	0.050
	SR 15			0.374	0.002
	Speed trill 1–3			0.292	0.030

Abbreviations as in Table 2.

Multiple regression analysis of level 5. The regression model for level 5 is different again (Table 14): trilling speed (Trill 3–4) re-enters as the first predictor accounting for 19.8% of model fit. Further improvement is reached by the inclusion of SR 15 in model 2 and an additional psychomotor speed variable (Trill 1–3) in model 3, which is the optimum solution and shows a model fit of 37.5%.

Discussion

Results from the data analysis indicate that different predictors gain or lose significance when SR complexity is increased. In accordance with our main assumption, this means that SR achievement can best be predicted by a level-dependent dynamic model, which is characterized by a combination of predictors. In other words, different musical and non-musical skills are necessary to accomplish diverse levels of SR complexity. The significance of the three groups of predictors (general cognitive skills, elementary cognitive skills and expertise-related skills) for the different levels of SR complexity are discussed in the next section.

General cognitive skills

Of the general cognitive skills, only the working memory capacity (WM) appears for level 3 in multiple regression analysis (Table 12). In correlation analysis for level 1, WM appears within the upper eight ranks (Table 4). For level 2, STM and WM play an important role (Table 5). In level 3 (Table 6) WM and STM, and in level 4 (Table 7), only Raven D has a significant influence. Finally, only the predictor STM from the group of general cognitive skills appears within the first 10 ranks at level 5 (Table 8).

Our interpretation of the predictors found is as follows: working memory test examines simultaneous storage and processing capacity; short-term memory tests the ability to store and recall information, and Raven's D is part of a test which is considered to be a good measure of general mental capacity. Thus the identification of variables from this group of skills shows that general cognitive skills play a role, and that in particular, working memory and short-term memory are significant predictors in this group. However, their influence changes and increases from level 1 to 3, but decreases from level 4 to 5. This means that when SR complexity is extreme, general mental capacity does not have the same weight as SR expertise or elementary cognitive skills, such as psychomotor speed or speed of information processing (for a presentation of the dynamic influence of predictors at different levels of task difficulty, see Figure 2).

Elementary cognitive skills

From the group of elementary cognitive skills, multiple regression analysis identified the following significant predictors: Trill 3–4 for levels 2, 3, and 5, Trill 1–3 for level

5, and speed of information processing (NCT) for level 4. Correlation analysis identified the following predictors: Trill 3–4 for all levels (Table 9); Trill 1–3 for levels 2, 3, 4, and 5 and tapping speed for level 3; both speed trills are significant for level 2, 3, 4 and level 5 (Figure 1).

How can we explain the salience of the trilling speed? All speed trills are significantly correlated with solo expertise, with correlations of $r = 0.53$ ($p = 0.00$) for Trill 1–3 and $r = 0.24$ ($p = 0.03$) for Trill 3–4. At first glance, this correlation could be interpreted as an indicator of general pianistic expertise (piano technique) based on extensive training. Correlation analysis between tapping speed (inter-tap interval) and trill speed revealed a moderate correlation of $r = 0.23$ for Trill 1–3 ($p = 0.04$) and $r = 0.22$ for Trill 3–4 ($p = 0.05$). Trill speed is, therefore, also related to general psychomotor movement speed and is interpreted as an intersection between a practice-dependent skill and a practice-independent skill, which indicates the subject's potential for neural optimization. However, despite these inter-relationships, an additional principal component analysis (Kopiez & Lee, in revision) revealed that trill speed together with tapping speed represents one factor and solo expertise another additional factor. This means that trill speed should be mainly interpreted as an independent 'psychomotor speed' factor, which is also related to general pianistic expertise.

To summarize, findings show that when SR complexity is very low, the demands on pianistic expertise and psychomotor speed are also low. When the complexity increases to a medium level, demands on elementary cognitive skills also increase. When SR complexity reaches its highest level, the variables 'speed of information processing' and 'psychomotor speed' from the group of elementary cognitive skills are needed to explain the high performance level. However, contrary to our initial assumption, reaction time and tapping speed are not significant predictors from this group of skills for the explanation of SR achievement.

Expertise-related skills

The significance of the window of time up to the age of 15 for the acquisition of SR expertise was one of the main findings of our previous study (Kopiez & Lee, in revision). In this study, multiple regression analysis confirms the role of expertise, but there are differences: at level 1, SR 10 contributes to the model fit; at level 2, acquired SR expertise does not seem to play a role; at level 3, SR total adds 4.0% to the model fit; at level 4 (Table 13) SR 15 contributes 13.8% and SR 18 contributes 6.8%; and at level 5 (Table 14) SR 15 contributes 12.7% to the model fit. For the first time, we found evidence that the skill of imagining the sound of a score can also be of advantage in SR. At level 4, inner hearing contributes 17.1% to the regression model.

Correlation analysis showed that SR 10, 15, 18 and total are significant predictors (Table 9) for levels 1 to 3, but at level 4 we can observe a shift of significance to the early acquired expertise, while SR 15 remains the only significant predictor. At level 5, SR 15 becomes the strongest single predictor ($r = 0.50$, $p = 0.00$).

To summarize, correlation analyses confirm the importance of expertise in SR excellence. However, SR 10 is not a very reliable predictor for expertise due to it being dominated by general piano skills, whereas SR 15 and 18 represent the years of specialization in accompanying, chamber music playing and SR, and are parts of the normal process of domain-specific skill acquisition. In contrast to the results of previous studies in SR (e.g. Lehmann & Ericsson, 1996), it is not the total amount of accumulated practice but the acquired expertise up to a certain age that is important. Our study reveals that the critical time window closes at the age of 15. When SR complexity is low, it does not challenge the SR expertise—the general pianistic expertise is sufficient to be able to sight read successfully. This interpretation is according to the model proposed by Lehmann and Ericsson (1993). With increasing complexity though, the general pianistic expertise is not sufficient and the years of expertise in SR are required to be able to sight read well. Most complicated SR pieces require a sufficient amount of SR 15 expertise and this indicates the importance of early specialization in becoming an excellent sight reader. However, we have to bear in mind that calculations of accumulated practice are based on retrospective interviews. From previous studies on expertise-related skills, we know that retrospective interviews on the amount of time spent on domain-specific practice are reliably reported by subjects. For example, Lehmann and Ericsson (1998) found that there is a high correlation between retrospective estimates of accumulated practice time and accumulated time from the subject's practice diary. An estimation error of only 10–15% was observed (for similar findings, see Ericsson *et al*., 1993; Krampe, 1994). In the most recent study, Bengtsson *et al*. (2005) were able to show, by means of a retrospective interview, that practice times reported by professional pianists for different phases of life have a high test–retest reliability if assessed 1 year later. Reliabilities of the measures of childhood, adolescent and adult practicing were $r = 0.81$, $r = 0.86$ and $r = 0.95$.

Inner hearing appears only at level 4 in multiple regression analysis, but in correlation analysis, it appears in the significant ranks for levels 2–5. The weight of this predictor increases as the complexity increases, but when SR complexity reaches its upper limit in our test, the influence of inner hearing decreases. Our explanation for this changing influence is that for the lower levels of task difficulty, inner hearing does not play a crucial role because general piano skills and acquired expertise are sufficient. Inner hearing unfolds its influence at level 4, but due to the lack of time to create an auditory image of highly complex music, the importance of this predictor decreases from level 4 to level 5. In other words: only when SR complexity is low or medium, is there enough time to audiate the written score, but if inner hearing is successful, it can improve SR. Our finding is supported by the study conducted by Waters *et al*. (1998). The authors found that auditory imagery was the third best predictor for SR achievement. They argue that inner hearing could serve as an auditory priming variable for the score to be played, thus enabling the player to acquire expectations about the piece's continuation. This interpretation is according to the model proposed by Lehmann and Ericsson (1993). Finally, we have to consider that our performance analysis is based on a restrictive 'score-matching paradigm'. We do not claim that this is the only possible criterion for SR evaluation, but we prefer this criterion due to its objectivity. We are also convinced that the number of correctly performed pitches is a necessary criterion for performance quality. However, evaluation of other performance features such as the aesthetic quality using rating methods could also be made (Kornicke, 1995).

General discussion

The main aim of this study was to reveal the relationship between the complexity of SR stimuli and predictor skills, in order to formulate a level-specific 'dynamic' model of SR. This main aim was achieved and against the background of our level-specific analyses, SR achievement can now be explained as a combination of speed of information processing, psychomotor speed and SR expertise. Of course, piano skills are not independent from each other and McPherson (1994, 1995; McPherson *et al*., 1997) states that the five skills of performing music (performance of rehearsed music, SR, playing from memory, playing by ear and improvising) are significantly inter-correlated, with the strength of these correlations ranging between $r = 0.64$ and $r = 0.77$. This indicates that there are no negative correlations, and that a good sight reader will be able to play from memory, play by ear, improvise and be a good performer. In our data, there are also only positive correlations between SR, pianistic expertise, inner hearing and short-term memory.

This investigation took the next step and delved into the depths of SR skill in order to understand the intricacy of the taxing demands on sight readers. SR prediction is dynamic due to the shifts in significance of predictors depending on the complexity of SR stimuli. In other words, demands on mental capacity, expertise or psychomotor skills are variable for different levels of complexity. We assume that this adaptive behaviour of the instrumentalist's brain reflects a basic feature of human information processing. The neurological system always uses the optimum activation pattern with respect to the task demands. Activation that is either too high or too low would be inefficient.

Finally, we are aware that our sample consisted of experts, but, nevertheless, we can draw conclusions about the demands on the instrumental beginner. If instrumental teaching trained all five sub-skills as proposed by McPherson's approach, we could be sure that SR skills would also be developed successfully. For example: playing by ear and improvisation is good training for inner hearing; scales and other technical exercises are good training for general pianistic skills; accompaniment of songs is good practice for SR. For the first three levels, these skills are sufficient to become a good sight reader. However, the only variable assumed to be non-practice-dependent is the speed of information processing. In our dynamic model of SR, this 'mental speed' factor enters regression analysis at level 4 (Table 13) and it also contributes significantly to the general model for the pooled achievement by 8% (Kopiez & Lee, in revision). We currently think that speed of information processing is an inherent advantage for the particular time constraints of a SR task. Our explanation is supported by recent intelligence research: as Mackintosh (1998, p. 242) argues, speed of information processing (as measured by an inspection time task) is highly correlated with the sub-test's loading on the *g*-factor of intelligence. With this background, a music-specific test for speed of information processing is not necessary. The more basic a test is constructed, the less it is influenced by training effects. Of course, training always causes optimization; however, task-specific training effects cannot be transferred to different tasks and thus only represent material-based effects. Thus, from our point of view, for a differentiated explanation of SR achievement, it would be adequate to consider practice-dependent as well as genetically determined abilities for the explanation of extraordinary musical skills. With this background, and in addition to the important role of acquired expertise, speed of information processing and psychomotor movement speed would be two variables that could contribute to a better understanding of exceptional musical skills.

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Sound examples, full scores of the SR tasks, a video of the procedure and a colour version of Figure 2 can be obtained from the website http://musicweb.hmt-hannover.de/sightreading

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