

MUSIC REHEARSAL INCREASES THE PERCEPTUAL SPAN FOR NOTATION

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DESPITE EVIDENCE FOR IMPROVED VISUAL PROCESSING of the printed score among skilled musicians, the effect of music rehearsal on the effective visual field (“perceptual span”) for a musical score has never been directly examined. Following 1-20 rehearsals, 11 skilled and 10 less skilled adult musicians reported whether a variant note appeared within a melodic sequence of 3-18 notes, presented onscreen for 200 ms in a tachistoscopic task designed to evaluate the perceptual span. Initially, skilled musicians showed a slightly larger perceptual span for challenging passages (5 notes vs. 4 notes for less skilled musicians). Perceptual spans increased incrementally in both groups, but skill differences in span size disappeared by 20 rehearsals (span of 11 notes). A correlation between improvements in visual perceptual span and performance speed suggests that perceptual learning could underlie early improvements in performance during music rehearsals.

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DOES MUSIC REHEARSAL IMPROVE THE RANGE OF notes that can be “instantaneously” perceived on a musical score? Does the range of notes perceived—either before or after rehearsal—depend on prior musical expertise? These issues are directly relevant to musicians who read music to increase their musical repertoire, accompany soloists, or perform in ensembles, but in a larger context, these issues are also important for understanding how our perception can be modified through experience.

Skilled performance of a difficult musical piece is attained through numerous repetitions or “rehearsals,” which are typically accompanied by improvements in speed and accuracy. Many factors contribute to these

performance improvements, including visual memory for the pattern of notes, auditory memory, and motor memory for the pattern of finger movements (Land & Furneaux, 1997; Palmer, 1997; Palmer & Meyer, 2000; Shaffer, 1981; Sloboda, 1984). Rehearsal might also improve performance through enhanced perception of the score, but this possibility generally is overlooked. The range of accurate perception for a score limits how quickly, accurately, and expressively the music can be performed on first viewing (unless the music is acoustically familiar and the musician is “playing by ear”). The range of accurate perception continues to play a limiting role until memory allows the musician to anticipate upcoming notes.

To avoid potential confounds from memory, studies on the visuospatial range of “instantaneous” perception in music have traditionally examined behavior during performance of unfamiliar musical scores with one of four techniques (Truitt, Clifton, Jr., Pollatsek, & Rayner, 1997). Each has its limitations. With one, musicians are asked to perform a melodic line following its tachistoscopic presentation (Bean, 1938; Sloboda, 1984; Van Nuys & Weaver, 1943) or after the lights are extinguished (Sloboda, 1985). A second technique identifies the average number of notes between fixations. A third technique identifies the “eye-hand span,” the discrepancy between the note being played and the eye position (Furneaux & Land, 1999; Gilman & Underwood, 2003; Goolsby, 1989, 1994a, 1994b; Sloboda, 1977; Truitt et al., 1997; Weaver, 1943). Using these first three techniques, estimates of the spatial range of “instantaneous” perception have varied from 1-8 notes. As reviewed by Truitt et al. (1997), the accuracy of each of these three techniques for estimating perceptual processes is uncertain, as estimates from each method may be affected by predictions based on knowledge of musical structure, phrase boundaries, memory decay, global visual cues, or overlap of visual information across fixations.

The fourth technique used to examine the spatial range of perception while reading music uses the gaze-contingent moving window paradigm to identify the “perceptual span,” i.e., the effective visual field for perception during a single fixation (Gilman & Underwood, 2003; Truitt et al., 1997). Studies on the cognitive control

of eye movements (McConkie & Rayner, 1975; Rayner, 1998) have demonstrated that the spatial range of “instantaneous” perception effectively reflects the visual processing that occurs within a single fixation. The moving window paradigm limits the number of notes that are in view, adding music as the eyes move ahead. Any window that interferes with eye movements or performance has intruded on the perceptual span; thus, the perceptual span is defined as the largest window for music preview that significantly distorts eye movement or performance parameters, delineated by the number of notes (or musical beats) displayed ahead of the current fixation. (Distortions are identified from statistical comparisons of eye movement / performance parameters with and without a restrictive window.) This technique has provided perceptual span estimates of 3 to 4 notes (or beats) to the right of the current locus of fixation, or 4 to 5 notes ahead of the point of performance (Gilman & Underwood, 2003; Truitt et al., 1997). This perceptual span estimate avoids some confounds inherent with other techniques, but still depends on measurements taken during musical performance. Eye movement parameters measured with this technique are similarly affected by factors such as musical note duration, tempo, phrases, and performance difficulty (Goolsby, 1989, 1994a, 1994b; Kinsler & Carpenter, 1995; Sloboda, 1984).

The techniques described above require the use of unfamiliar music, as performance of familiar music from memory would improve performance and lead to exaggerated perceptual span estimates. The effect of *rehearsal* on the spatial range of perception of visual notes is unknown, as is the time frame over which such effects might become evident. Rehearsal need not have any effect on visual perception of music, as memory for the passage might be sufficient for the observed improvements in performance. It also is possible that familiarity through rehearsal reduces reliance on notation, with familiar chords and note sequences filled in from fewer notational elements; this could explain why the rate of proofreaders’ errors in music increases with skill level in musicians (Sloboda, 1984, 1985). Alternatively, familiarity through rehearsal might improve the perceptual span for music, similar to the familiarity effect for increasing the perceptual span for common vs. uncommon words (Henderson, Dixon, Petersen, Twilley, & Ferreira, 1995; Inhoff, 1989; Rayner, 1986a).

If the perceptual span for music does change with familiarity, the time frame over which this perceptual learning might occur is unknown. Among children, the perceptual span for reading text is greater among skilled readers (Lovett, 1984; Rayner, 1986b), who can

read faster and more fluently than less skilled readers. Extensive training can take several weeks or months to improve reading fluency (Coyne, Kame’enui, Simmons, & Harn, 2004; O’Shaughnessy & Swanson, 2000; Reynolds, Nicolson, & Hambly, 2003; Vadasy, Sanders, & Tudor, 2007). Because the perceptual span and reading fluency are measured while reading unfamiliar text that contains familiar words, the improved perceptual span or fluency scores after extensive training are likely to reflect improvement on many individual words. Fluency (speed) of musical performance improves quickly through rehearsal as an unfamiliar musical passage becomes familiar, so associated changes in perceptual span might occur over a few rehearsals. Rehearsals improve the skill for performance on a specific passage, but the effect of prior *musical skill* on the initial perceptual span and rehearsal-related changes is unknown.

In the current study, we explore the perceptual effects of musical expertise and familiarity through 20 rehearsals, and examine the potential relationship between the perceptual span and maximal performance speed. Musical performance-related effects on the perceptual span were avoided by using a forced-choice design in a tachistoscopic error-detection task. We hypothesize that improved familiarity through rehearsal will produce an increase in the perceptual span, and that increases in the perceptual span will be correlated with improvements in maximal performance speed for difficult musical passages.

Method

Participants

Informed consent was obtained from 21 adults, ages 20–45, using procedures approved by the Institutional Review Board at Northwestern University. Participants were tested on a perceptual span task following rehearsal on an electronic keyboard; the direction of gaze and musical performance of four of these participants was videotaped for additional analyses. Nine additional participants were tested on a control task (described later), including three who were musically illiterate (incapable of reading musical notation).

Our selection of participants for this study was intended to accentuate differences in musical skill in order to more clearly demonstrate group differences in perceptual span. Participants were recruited and tentatively classified based upon their music training; skilled musicians had collegiate musical instruction, less skilled musicians had no more than five years of musical instruction on their instrument. Musical skill was

then evaluated through musical performance while sightreading. Consistent with our intent, skilled musicians (seven males, four females) were identified whose music training and sightreading abilities exceeded, without overlap, those of our less skilled musicians (six males, four females). Skilled participants had relatively short performance times on a test passage (mean = 98 ± 23 s, range = 75-120 s), reflecting 13.8 ± 5.1 years of formal music training. Ten less skilled participants (six males, four females) had longer performance times on the test passage (mean = 229 ± 54 s, range = 165-285 s).

General Procedure

Based upon each participant's musical background and demonstrated sightreading ability, one of two unfamiliar musical passages was assigned as a challenging rehearsal passage. Some skilled musicians were additionally assigned the easier passage for rehearsal at a later time.

Prior to the first rehearsal, participants were informed of the purpose and general approach of this study. Without prior examination of the music, participants were instructed to rehearse the assigned passage once as rapidly as possible from beginning to end without stopping, and that immediately after rehearsal, they would be tested on their ability to recognize a sequence of notes from some part of the rehearsal passage. Participants were not told which part of the musical passage would subsequently be used for perceptual testing. In the standard procedure, participants were tested immediately after the first rehearsal on day one and after the final rehearsal in each subsequent rehearsal session.

Rehearsal sessions occurred on different days, typically 2-3 days apart. Different groups of participants were given different rehearsal schedules. One group rehearsed twice per session for 10 sessions, another group 3-4 times per session for seven sessions, and a third group 4-5 times per session for four sessions. Each group included both skilled and less skilled musicians. For each rehearsal schedule, participants were tested after the first, tenth, and twentieth rehearsals; results are reported from tests following these rehearsals.

For the perceptual task, participants were told that a sequence of notes from their rehearsed passage would briefly flash onscreen at the left edge of a staff; the same musical phrase would always be tested, and the sequence of notes would differ from the rehearsed passage by one note at most. Participants were instructed to press one key if the sequence of notes that flashed onscreen matched the rehearsed passage, and another key if it did not, responding as quickly as possible without sacrificing

accuracy. Although guessing was encouraged, participants were instructed to respond the same ('match' or 'not match') whenever the same sequence of notes appeared. (Each variant sequence—as well as the target sequence—appeared multiple times during a test session.) These instructions encouraged responses based on perception even when the specific target sequence of notes was not recalled from the rehearsal.

Participants were not given feedback about performance accuracy during rehearsals or during testing. Following the first test session, participants were asked whether they remembered from their rehearsal the sequence of notes appearing in the perceptual task.

Rehearsal Passages

Each participant rehearsed at least one of two musical passages. The "easy" passage was rehearsed by all 10 less skilled musicians and seven skilled musicians; this original one-page passage included 29 measures of a single melodic line in the key of D major (see Figure 1A). The shortest note values in the "easy" passage were eighth notes in 4/4 time; many notes were repeated or adjacent to each other. The "difficult" musical passage was unfamiliar prior to its rehearsal by all skilled musicians; this one-page musical passage consisted of 15 measures from Liszt's Etude No. 5 (from the Twelve Transcendental Studies). The shortest note values in this passage were thirty-second notes in 2/4 time. Parts of this passage consisted of a single melodic line in the treble clef, accompanied by rests in the bass clef (see Figure 1B). The melodic line of the "difficult" passage consisted of 176 notes, compared with 150 notes for the "easy" passage.

Experimental Stimuli

For all participants, a single melodic line from their rehearsed passage was used as the target sequence for perceptual testing. The target sequence consisted of 18 notes that were rapid and of equal duration; experimental stimuli in the perceptual test consisted of 3-18 notes from this target sequence, always starting at the beginning of the sequence. A single note was replaced in *variant* sequences.

Musical notation software (Encore) was used for generating stimuli; a screen snapshot was taken of the stimulus and cropped so that all stimuli could be precisely aligned across trials. Horizontal spacing between notes differed across passages due to differences in the location of accidentals and barlines, but horizontal spacing through the first 14 notes never differed

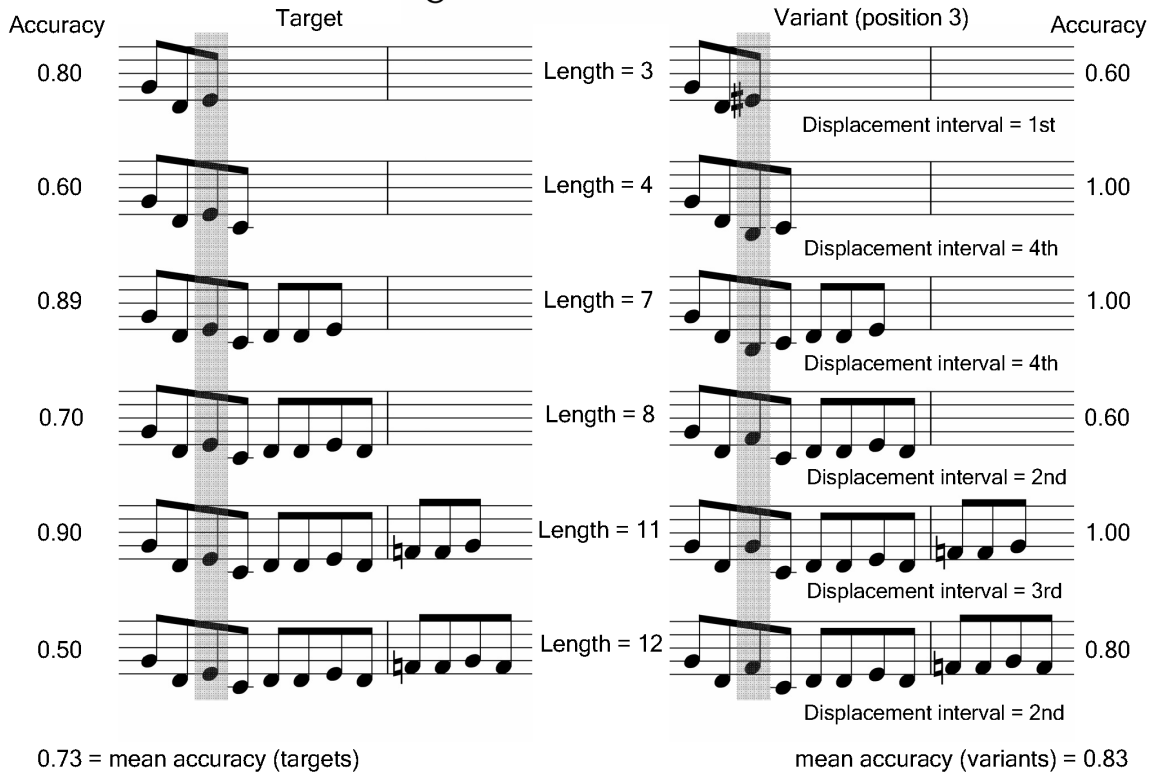
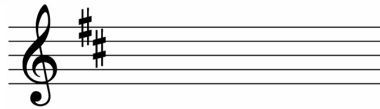
A Rehearsal passage A

Allegro vivace



Perceptual test

Key signature



$$\text{Accuracy index (position 3)} = \frac{\text{mean}(\text{targets}) + \text{mean}(\text{variants})}{2} = \frac{0.73 + 0.83}{2} = 0.78$$

FIGURE 1. *Rehearsal passages, sample sequences, and calculation of an accuracy index from the perceptual test.* A: Four lines of the rehearsal passage and sample trials from the perceptual test for less skilled musicians. The key signature presented at the beginning of a perceptual test was followed by a series of trials, each presenting one target or variant note sequence. For each note position, the mean accuracy of the variant and target sequences of the same length were averaged to create an accuracy index, here illustrated for position 3. The note position for each variant is highlighted and the interval step of displacement from the target note is specified. B: Two lines of the rehearsal passage and sample trials from the perceptual test for skilled musicians. The sample variants shown here are for position 4.

B Rehearsal passage B

Equalmente

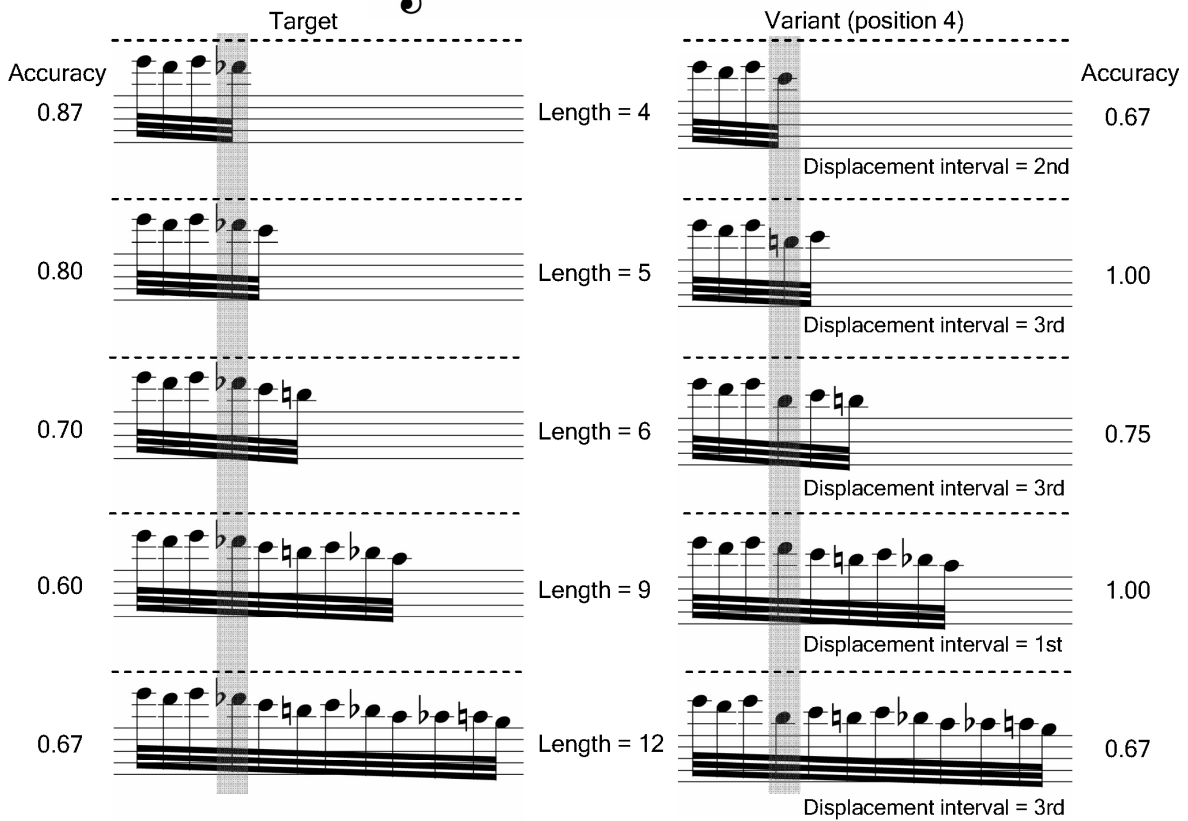
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Perceptual test

Key signature



0.73 = mean accuracy (targets)

mean accuracy (variants) = 0.82

$$\text{Accuracy index (position 4)} = \frac{\text{mean}(\text{targets}) + \text{mean}(\text{variants})}{2} = \frac{0.73 + 0.82}{2} = 0.77$$

FIGURE 1B.

between passages by more than one note. Furthermore, the position and angle of musical elements (barlines, accidentals, beaming, etc.) was kept constant (see Figure 1). The mean horizontal distance between notes provided a visual angle of 1° at a typical viewing distance of 45 cm.

Although sequences were variable in length, the beginning of the sequence always appeared near the left edge of the staff, implicitly encouraging participants to use it as a reference point. For each stimulus length, four variant sequences were used; thus, every possible combination of sequence length and variant position did not occur. To ensure that participants attended throughout each stimulus, the note position of variants was staggered across sequences of similar (but different) lengths so that the length of the sequence would not be a useful cue for variant location. This approach was deemed preferable to the alternative of using one long sequence with variants appearing randomly at each position, which would have negated the advantage of consistently attending to stimuli near the left edge of the staff.

The same combinations of variant position and sequence length were used for all participants. Nonetheless, differences in contour and position of the notes on the staff between the “easy” and “difficult” target sequences necessarily resulted in different musical characteristics of variants used for each passage. Variant characteristics are summarized in Table 1.

Standard Perceptual Task

Stimulus presentation and recording of participant responses were controlled by a Macintosh laptop computer via PsyScope, with a screen refresh rate of 16 ms.

TABLE 1. Musical Characteristics of the Variant Stimuli.

Variant Trait	Passage A (“easy”)	Passage B (“difficult”)
Change in contour*	42.4%	36.5%
Interval of displacement†		
Accidental only	9.1%	22.2%
Second	50.0%	33.3%
Third or greater	40.9%	44.5%
Direction of displacement		
Upward	53.0%	22.2%
Downward	37.9%	55.6%
Neither (accidental)	9.1%	22.2%

*Frequency of changes across all trials in the position of the musical nadir or zenith appearing within the presented sequence.

†Diatonic interval of variant note position relative to the original target note. The category for “third” intervals was used as an overflow bin for passage A (but not passage B), incorporating 4.5% for musical fourths and 3.0% for fifths.

The key signature of the target passage was presented once at the beginning of each test session, followed by the test trials. Each trial began with the appearance of a musical staff, followed 500 ms later by the experimental stimulus. On one-third of the trials, the experimental stimulus matched the target sequence from the rehearsal passage (for however many notes were presented); on the remaining trials, a single note from the target sequence was replaced with a variant note. The experimental stimulus was presented for 200 ms, and was aligned so that the notes appeared to flash onto a stationary staff. The experimental stimulus was then replaced by the empty musical staff, the white background of the staff eliminating any visible persistence of the black notes on the computer display.

The perceptual test consisted of 245-270 trials, performed over a span of 12.25-13.50 minutes. Three to 18 notes appeared on any trial, with stimuli presented in random order; each trial’s duration was 3.0 s. On alternate testing sessions, participants were presented either odd-numbered (3-, 5-, . . . 17-note sequences) or even-numbered sequences (4-, 6-, . . . 18-note sequences). The order of presentation was counterbalanced across participants.

Control Tasks

In order to rule out alternative explanations for rehearsal effects on perceptual span, four variations of the standard experimental design were presented. These control conditions explored: (1) potential learning effects from test sessions; (2) perceptual accuracy relative to gaze; (3) effects of restricting gaze; and (4) effects of a poststimulus mask. The fourth control condition was carried out in a separate group of nine participants (four skilled, two less skilled, and three musically illiterate); each of the others was carried out in its own subgroup of the 21 participants whose results are illustrated in this report.

LEARNING EFFECTS FROM TEST SESSIONS

To exclude potential learning effects from the test sessions themselves, the initial perceptual test was administered after 20 rehearsals in four participants (one skilled, three less skilled).

PERCEPTUAL ACCURACY RELATIVE TO GAZE

The eye position of four skilled musicians was monitored during rehearsals and perceptual tests with a head-mounted infrared eye tracker (Iscan, 120 Hz sampling rate). This allowed us to determine if gaze moved during stimulus presentation, to identify variant

locations relative to the direction of gaze, and to determine if changes in perceptual span measurements across testing sessions might actually reflect strategic changes in gaze.

The point-of-regard eye signal was calibrated using a 9-point calibration array with the participant's head stabilized on a chinrest. The position of gaze was averaged from two consecutive time points to reduce jitter, superimposed on a video display of the scene, and recorded on videotape for offline analysis. During the perceptual test, the note nearest the position of gaze at the time of stimulus presentation was identified for each trial; the videotape was advanced frame by frame to determine whether the gaze moved to a new location during stimulus presentation. The accuracy of the participant's response and the variant's position relative to the direction of gaze were additionally recorded on variant trials.

EFFECTS OF RESTRICTING GAZE

For some participants (five skilled, four less skilled musicians), the background staff included a 3° solid fixation spot, centered at the initial note position. Participants were instructed to look at this fixation spot until the music appeared, then to indicate whether the music sequence was the target or a variant.

Overall, this group of participants was tested following rehearsals 1, 4, 7, 10, 13, 16, and 20. The control condition followed the seventh rehearsal only; to evaluate the effect of restricting gaze, the results were compared with those of the subsequent test session (following the tenth rehearsal).

EFFECTS OF A POSTSTIMULUS MASK

To explore the potential role of iconic memory, the perceptual span task with a poststimulus mask was presented to nine additional participants after 1, 10, and 20 rehearsals; four were skilled musicians, two were less skilled musicians, and three were musically illiterate. Musically illiterate participants "rehearsed" by looking at the sequence of notes in the easy passage (Figure 1A) from beginning to end for 3-5 minutes (comparable to the initial time of rehearsal on the same musical passage by less skilled musicians).

The mask consisted of a four-note chord of thirds that replaced each note in the test stimulus and remained onscreen for the remainder of the trial; this chord extended across the vertical range of notes presented in the target sequence. This mask avoided the introduction of an additional visual landmark that could have been used on variant trials to demarcate a change in note position.

Data Analysis

ACCURACY ESTIMATES FOR INDIVIDUAL VARIANTS

For each variant, an accuracy index was calculated to identify how well a participant was able to differentiate between the variant and the target sequence of the same length. This index was calculated as the percentage of correct responses for variant trials averaged together with that for target trials. This accuracy index is indifferent to response strategies that are not based on perception; e.g., the accuracy index remains near the chance value of 50% if a participant responds randomly or responds "target" to all stimuli.

In its insensitivity to response strategies, this approach is similar to d' used to characterize the discriminability of a signal from noise. Our approach, however, does not require the assumption that all variants at a position are equally salient, and minimizes the potential confound of sequence length on positional effects.

OUTLIER TREATMENT

Our goal was to estimate perceptual performance from the mean accuracy index of variants appearing at each note position. When many variants appeared at a position, a single variant with unusually high (or low) salience would have limited effect on the average accuracy index for that position. Later note positions were more sensitive to outliers because fewer variants necessarily appeared at later note positions; for example, a variant at position 10 required sequences at least 10 notes in length, whereas variants could appear in the first three positions regardless of sequence length. The first three positions had the highest overall incidence of variants (11.1%, 14.3%, and 14.3% of variant trials), with a progressive decline in incidence evident over the next three note positions (9.5%, 7.9%, and 6.3%). Incidence of variants at positions 7-13 fluctuated between 3.2%-4.8%. Variants after position 13 were not included in statistical analyses because of their lower incidence and because few alternative variants were presented.

Outliers considered for removal were limited to later positions, beginning with position five, due to their greater potential for inflating the accuracy index. (Fewer variants were presented after position five.) Data for a variant was removed if its accuracy index was one standard deviation above or two standard deviations below the mean of all variants appearing at position five or later from an individual's test session. The mean number of variants removed was 1.5 ± 1.3 (out of 60 possible variants), and the mean note position of variants removed was 7.9 ± 2.4 . No differences in the number or note position of variants removed were evident across sessions.

ACCURACY ANALYSES

Accuracy indices were averaged from all variants appearing at each note position. Data were further smoothed by averaging the accuracy index from each note position with that of the preceding note position, thereby reducing potential procedural effects arising from participant differences in variant position/length combinations presented in a test session. A least-squares regression procedure was used to fit data to a Gaussian or exponentially modified Gaussian curve and to identify the confidence intervals (using the software Table Curve 2D). The perceptual span was delimited by the range of note positions where the 95% confidence intervals surrounding the regression curve were > 52%.

Group comparisons at individual note positions were additionally made at individual note positions using a two-tailed *t*-test. Because results from the two methods of analysis generally were consistent, results from the *t*-test analyses are reported only when useful for interpretation.

CORRELATION ANALYSIS

For nine participants (five skilled, four less skilled), the time of performance on the rehearsal passage was recorded. The Pearson correlation was computed from the relationship between the percentage decrease in performance time to the percentage increase in perceptual span across rehearsals. The statistical significance of this correlation was calculated using a one-way ANOVA applied to the resulting regression line.

Results

Music Rehearsals and Participant Feedback

PERFORMANCE AND EYE MOVEMENTS DURING MUSIC REHEARSALS

No participant became proficient at performing the rehearsal passage in this study, evident from the halting

nature of the performance as well as the slow tempo still observed at the twentieth rehearsal (see Table 2). Furthermore, internote time intervals for the target passage were initially variable and remained variable through the twentieth rehearsal.

For the four participants whose gaze was monitored during music rehearsals, the mean fixation rate in measures with a single melodic line varied little from the first to twentieth rehearsal (Table 2). The low fixation rate indicates that participants tended to look at each note at least once before continuing to the next note. Even after 20 rehearsals, two or more notes/fixation had been observed for only 0.7% of the measures performed.

PARTICIPANT FEEDBACK

Participants were asked for feedback following the first test session. Participants were not forewarned about the location of the target sequence within the rehearsal passage, and as expected, no participant could recall the observed sequence of notes from rehearsal. Nonetheless, they invariably reported that they could identify correct notes during the perceptual test based upon which note appeared most frequently at a position.

Perceptual Span for Unfamiliar Music After Rehearsal 1

EQUATING MUSIC DIFFICULTY

The initial performance time on the one-page "easy" passage by less skilled musicians did not significantly differ from performance time on the one-page "difficult" passage by skilled musicians (see Table 2). Performance times also did not differ significantly between groups after 10 or 20 rehearsals.

PERCEPTUAL SPAN ESTIMATES

The perceptual span following the first rehearsal is shown for the group of skilled and less skilled musicians (Figure 2A) and for select individuals from each

TABLE 2. Performance Parameters at Beginning and End of Experiment.

	Rehearsal 1		Rehearsal 20	
	Less skilled	Skilled	Less skilled	Skilled
Rate of note production* (notes/s)	—	0.5–2.9	1.8–4.5	3.7–5.2
Internote time intervals (standard deviation, ms)	144–253	55–374	24–104	61–78
Performance time (s) (SD)	2'43" (43")	3'54" (2'49")	1'32" (17")	1'22" (50")
Fixation rate (mean) (notes/fixation)	—	0.76	—	0.93

*Mean rate of note production identified from measures with a single melodic line.

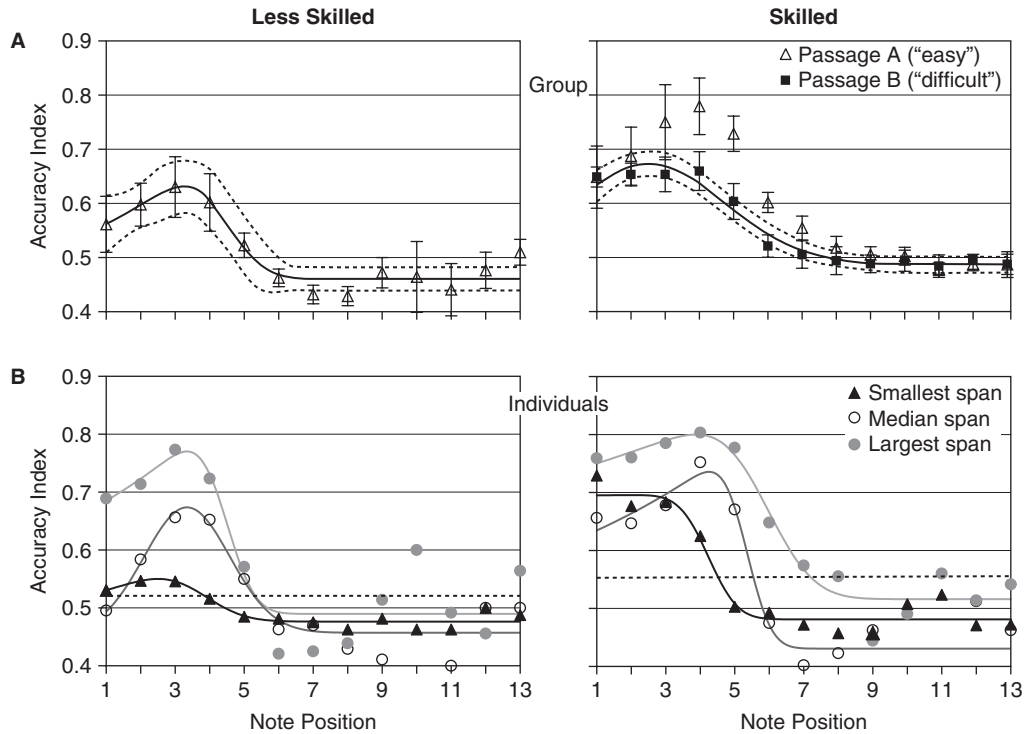


FIGURE 2. *Perceptual span measurements after the first rehearsal for skilled and less skilled musicians. Accuracy indices are plotted as a function of variant position. A: Group accuracy on passage A by seven less-skilled musicians (left) and seven skilled musicians (hollow triangles, right), plus accuracy on passage B by the entire group of 11 skilled musicians (solid squares, right). Dotted lines represent the 95% confidence intervals surrounding the regression line; standard error bars surround the mean accuracy index (± 1 S.E.). B: Accuracy for representative individuals in each skill group. Dotted lines represent the cutoff for the perceptual span (here derived from the individual with the maximal perceptual span).*

group (Figure 2B). The perceptual span for less skilled musicians on the “easy” passage (group span of 4 notes, individual range of 3 to 5 notes) was slightly smaller than for skilled musicians on the difficult Liszt passage (group span of 5 notes, filled squares; individual range of 4–7 notes). For the subgroup of skilled musicians who also rehearsed the “easy” passage, the perceptual span was even larger, extending to 7 notes (right graph in Figure 2A, hollow triangles).

EYE MOVEMENTS DURING PERCEPTUAL TESTS

Perceptual span estimates might be too large if participants were able to redirect their eyes to a second note position. Although participants reported that they never were able to move their eyes to a new note position before the stimulus disappeared, the eyes were redirected to a new note position on 1.5%–13.7% of the trials (among those four individuals whose eye movements were monitored). The new eye position always was attained during the final 25 ms of stimulus appearance (the final 12.5% of the total stimulus duration). The direction of these redirecting saccades on variant trials bore no consistent

relationship to variant position, and only 0.1% of trials had a correct response following a premature saccade when the variant was initially outside the perceptual span (as defined from trials with sustained fixation). Based on this analysis, no attempt was made to exclude data from trials with premature saccades.

Increased Perceptual Span with Rehearsal

REHEARSAL EFFECTS DURING STANDARD TESTING PROCEDURES

Incremental changes were observed in the spatial extent of perception following multiple rehearsals. Following the tenth rehearsal, perceptual span estimates had expanded for both skilled musicians (from 5 to 8 notes) and less skilled musicians (from 4 to 7 notes). By the twentieth rehearsal, the perceptual span had further expanded to 11 notes for both groups (Figure 3A); the range of perceptual spans was 10–11 notes among individuals from both groups (Figure 3B).

Rehearsal of the musical passage produced a mean decrease in performance time of 25.9% by the tenth

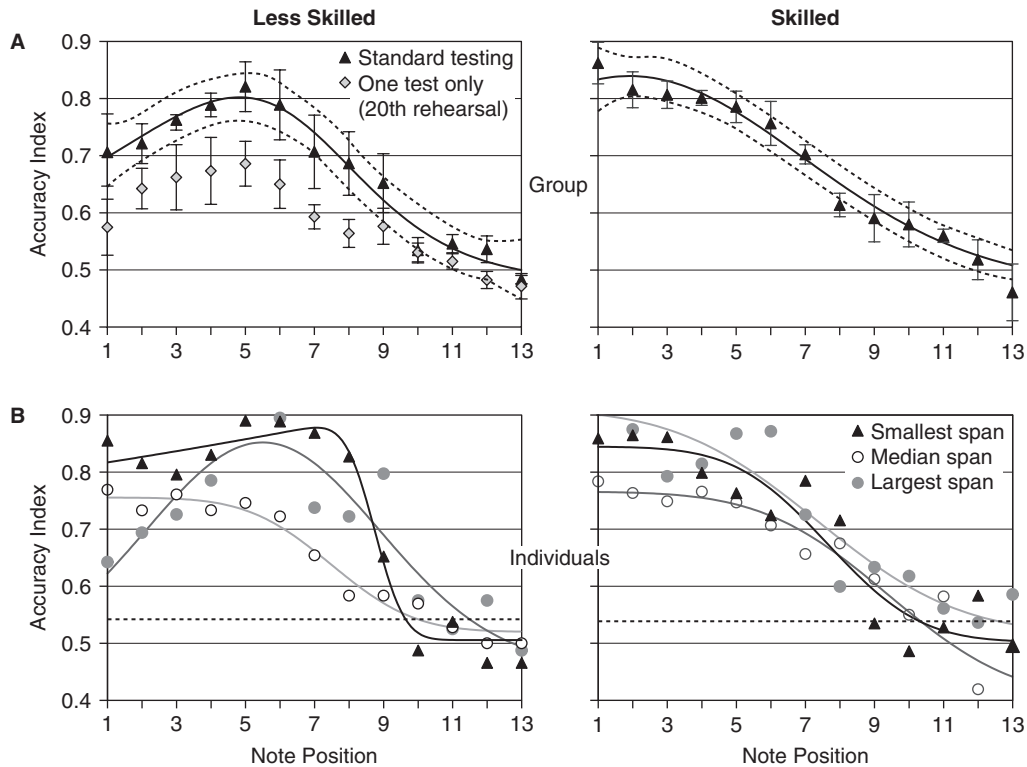


FIGURE 3. *Perceptual span measurements after 20 rehearsals.* Accuracy indices are plotted as a function of variant position following the twentieth rehearsal. A: Group accuracy by seven less skilled musicians tested after each rehearsal session and three less skilled musicians first tested after the twentieth rehearsal (left), plus the group of 11 skilled musicians tested repeatedly on the difficult passage (right). B: Accuracy for representative individuals in each skill group. Dotted lines represent the cutoff for the perceptual span.

rehearsal and 51.1% by the twentieth rehearsal. The percentage increase in the perceptual span across rehearsals was significantly correlated with the percentage decrease in performance time, $r(11) = .54, p = .03$.

CONTROL CONDITION: LEARNING EFFECTS FROM TESTING SESSIONS

Four less skilled participants were administered their first perceptual test after 20 rehearsals. Compared to the group of participants tested more frequently, the percentage accuracy after 20 rehearsals was reduced by as much as 13.9% at a position but the perceptual span was similar to that of the other participants (left graph in Figure 3A, gray shaded diamonds).

CONTROL CONDITION: PERCEPTUAL ACCURACY RELATIVE TO GAZE

In theory, participants could learn to strategically shift their direction of gaze across test sessions, which could artificially inflate our spatial estimate of accurate performance. This could occur, for example, if a participant initially limited his gaze to the left, where the first

4-5 notes could be identified; by gazing progressively further to the right on some proportion of the trials during later test sessions, above-chance performance could be achieved for additional note positions without any change in perception. To address this possibility, accuracy in identifying variants was measured from the direction of gaze for four participants.

Measured as a function of variant eccentricity from the direction of gaze, the range of notes where accurate identification of variants was better than chance ($> 50\%$) increased incrementally from 5 notes initially to 11 notes after 20 rehearsals (Figure 4A). This pattern mirrored the increases in perceptual span measured without regard to the direction of gaze (Figure 4B). Thus, the measured increase in perceptual span did not arise incidentally from strategic changes in the direction of gaze across testing sessions.

Measured from the direction of gaze, the perceptual span extended progressively to the right even though gaze was more restricted towards the beginning of the note sequence during later test sessions (Figure 4C).

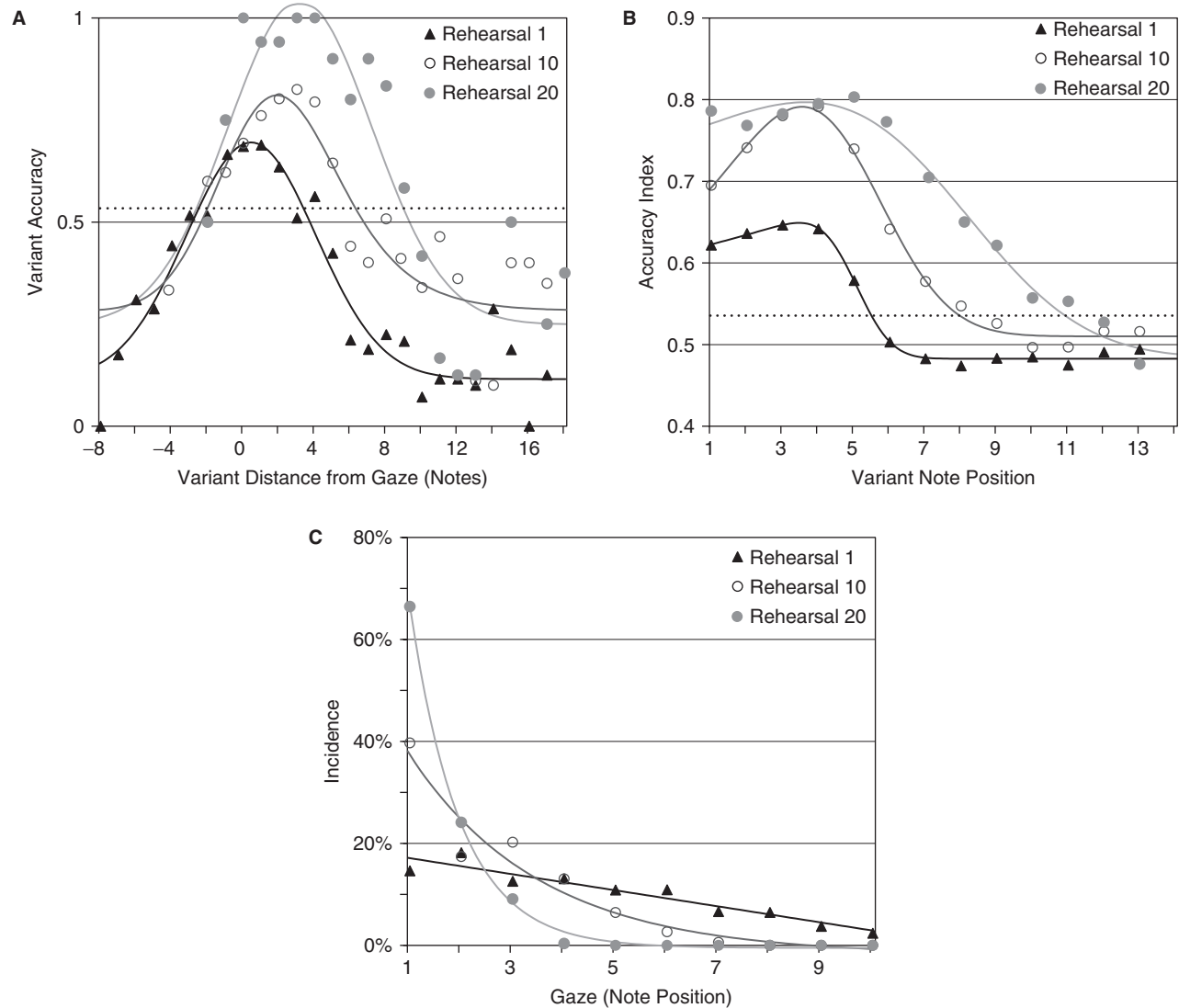


FIGURE 4. *Changes in perception and direction of gaze following rehearsal.* A: Accuracy for variant notes relative to the direction of gaze by the subgroup of four skilled musicians whose eye movements were monitored. Dotted line = threshold for above-chance performance based upon 95% confidence intervals. B: Accuracy index of the same participants irrespective of gaze. C: Direction of gaze during the perceptual task.

CONTROL CONDITION: EFFECTS OF RESTRICTING GAZE

Nine participants (five skilled, four less skilled) were tested prior to the tenth rehearsal while gaze was restricted to the solid fixation spot. Restricting gaze had no measurable effect on the perceptual span. Furthermore, there was no significant change in accuracy within the perceptual span when gaze was again unrestricted (mean increase of $3.4 \pm 1.6\%$ following rehearsal 10 among skilled musicians on the hard passage, mean decrease of $1.5 \pm 2.7\%$ among less skilled musicians on the easy passage).

CONTROL CONDITION: EFFECTS OF A POSTSTIMULUS MASK

The results of a mask for skilled and less skilled musicians are described here; experimental results for musically illiterate participants are described later.

With a poststimulus mask, the group of four skilled musicians showed a collective perceptual span of 6, 8, and 10 notes following the first, tenth, and twentieth rehearsals, respectively; the two less skilled musicians had respective span values of 6, 6, and 9 notes. Every individual in each group showed an increase in perceptual span from beginning to end of rehearsals. After the

final rehearsal, participants were tested with and without the mask; the perceptual spans under the two conditions were indistinguishable.

Effects of Musical Skill on Perception

SKILL DIFFERENCES IN SIGHTREADING PERFORMANCE

The two skill groups showed nonoverlapping performance times during their initial (sightreading) performance of the “easy” passage. This passage was more readily performed by the skilled musicians ($1'3'' \pm 17''$) by skilled vs. $2'43'' \pm 43''$ by less skilled musicians, $t(9) = 3.69$, $p < .01$.

SKILL DIFFERENCES IN PERCEPTUAL SPAN

As noted above, a slightly smaller perceptual span was observed for less skilled musicians (4 notes) than for skilled musicians on the difficult passage (5 notes). Planned comparisons of group means revealed a marginally significant difference only at the fifth note position, $t(11) = 1.84$, $p = .07$. Following the tenth rehearsal, perceptual span estimates were still slightly greater for skilled musicians (8 notes vs. 7 notes for less skilled musicians). Direct statistical comparisons revealed no group differences at individual note positions, however, and the mean difference in accuracy at position 8 was modest (3.8%). By the twentieth rehearsal, perceptual span differences between skilled and less skilled musicians had disappeared (span of 11 notes for each).

In addition, three musically illiterate participants “rehearsed” by inspecting a musical passage from beginning to end. Group analysis failed to demonstrate better than chance performance during any testing session for these participants, so data also were analyzed separately for these individuals. Two of these participants had never learned to read music, and performed at chance for every note position across all test sessions (after 1, 10, and 20 rehearsals). The third participant performed music as a child but had forgotten how to read musical notation; this participant had a perceptual span of 4 notes that remained stable over 20 rehearsals.

Discussion

This study explored three issues about perception of notation in musicians. First, the perceptual span was measured with a tachistoscopic error-detection task that avoided potential confounds associated with simultaneous musical performance. Spans of 4-5 notes found here were largely consistent with previous reports that used performance-based measurements (which found spans of 3-5 notes). Second, music

rehearsals were shown to produce incremental increases in the perceptual span for the rehearsed music, consistent with our hypothesis. Perceptual span/performance speed correlations suggest that these increases in perceptual span during relatively early stages of music rehearsal may help mediate improvements in musical performance, especially for difficult musical passages. Third, effects of musical skill on the perceptual span were examined. Skilled musicians initially perceived more notes than less skilled musicians; when the musical passage was sufficiently challenging, however, differences in perceptual span were initially modest and disappeared after 20 rehearsals.

Perceptual Span for Unfamiliar Music

IDENTIFYING THE PERCEPTUAL SPAN

Participants were instructed to make consistent guesses based upon what was seen. Given the constraint that no more than one variant would appear on any trial, the note appearing most frequently at each position was necessarily correct. (Because the most frequent incidence of variants at a position occurred on 14.3% of trials, for example, the correct note appeared at each position on at least 85.7% of the trials.) Use of these perceptual cues allowed accurate performance among participants who had no recollection of the target sequence following their first rehearsal.

The perceptual span for groups and individuals was estimated from the 95% confidence interval surrounding the modified Gaussian regression curve as fit to the behavioral data. This regression approach provides an estimate based upon performance across a range of positions, thereby reducing the potential effect of measurement errors at a specific note location. For group data, this 95% confidence interval approximated the standard error bars surrounding each data point, particularly where accuracy was elevated above 50% (see Figures 2 and 3).

PERCEPTUAL SPANS MEASURED WITH DIFFERENT TECHNIQUES

As noted in the introduction, previous estimates of the spatial range of “instantaneous” perception have ranged from 1-8 notes, but the effect of performance factors on these previous span estimates is unknown. Using our regression analysis on data from the tachistoscopic task, we estimate a perceptual span of 4 notes for the group of less skilled musicians (individual range of 3-5 notes), 5 notes for the group of skilled musicians on the difficult passage (range of 4-7 notes), and 7 notes for the group of skilled musicians on the easier passage shared with

the less skilled musicians (range of 6-8 notes). These findings are most similar to the combined “eye-hand span plus perceptual span” demonstrated with the moving window technique, with a combined span of 5 notes among skilled musicians and 3 notes among less skilled musicians (Rayner & Pollatsek, 1997). These similar results suggest that musical performance issues had little effect on previous perceptual span estimates using the moving window technique.

Using the eye-hand measure of perception, some studies have demonstrated a perceptual span of 6-8 notes among skilled musicians (Sloboda, 1982; Weaver, 1943). In our study, the initial perceptual span of skilled musicians was 7 notes after sightreading the easy musical passage, and expanded from 5 notes initially to 8 notes following 10 rehearsals on the challenging passage. These findings suggest that the size of the perceptual span among skilled musicians depends on their familiarity with local note patterns within the music. A similar effect of familiarity on the perceptual span for words has been reported, with a larger perceptual span for familiar than unfamiliar words (Henderson et al., 1995; Inhoff, 1989; Rayner, 1986a).

Changes in Perceptual Span with Rehearsal

IMPROVEMENT IN PERCEPTUAL SPAN

For both skilled and less skilled musicians, the number of notes that could be correctly identified from a musical passage increased following music rehearsals. Previous studies have demonstrated that as familiarity increases, fixations become shorter (Henderson & Ferreira, 1990; Hyona & Olson, 1995; Inhoff & Rayner, 1986), fewer fixations are required to recognize a pattern (Reingold, Charness, Pomplun, & Stampe, 2001), and fewer elements may need to be utilized for pattern identification (Goldstone, 1998). The current study shows that familiarity through music rehearsal actually *increases* the number of elements in a musical pattern that can be perceived within the timeframe of a single brief fixation.

The improved span following music rehearsal reflects an expanded area of perception rather than strategic changes in gaze. In this study, the perceptual span did not change with restricted fixation, and it increased across rehearsals relative to the direction of gaze. Furthermore, the improvement in perceptual span resulted from the music rehearsals rather than the test sessions, as the perceptual span was enlarged following 20 rehearsals regardless of the number of intervening test sessions. Although the *reliability* of accurate perception at each note position may have varied across

test conditions, stimulus characteristics, or musical skill, all participants who knew how to read music showed improvement in perceptual span following music rehearsals.

The perceptual span in this study was tested for only one specific part of the rehearsed score. The expanded perceptual span following rehearsal is likely to be specific to the rehearsed score. Subsequent testing on an unrelated musical passage has not shown a comparably enhanced perceptual span; this was apparent in this study when skilled musicians showed a perceptual span of 7 notes after the first rehearsal on the easy passage (passage A) after earlier reaching a perceptual span of 11 notes on a difficult passage (passage B). Subsequent testing on a second unfamiliar, challenging passage resulted in a perceptual span similar to those reported here, namely, 4-5 notes (unpublished observation).

ROLE OF PERCEPTUAL LEARNING

The demonstrated effects of rehearsal on perceptual accuracy demonstrated in this study reflect changes in the perceptual span. Observed changes in accuracy did not reflect changes in eye movements; the stimulus duration of 200 ms used in the tachistoscopic task represents the low end of fixation durations when performing music (Goolsby, 1989, 1994a, 1994b; Kinsler & Carpenter, 1995; Waters, Underwood, & Findlay, 1997), and an increased perceptual span was observed when measured relative to the direction of gaze.

Two sets of observations indicate that the improved span observed in this study did not result from improvements in explicit recall of the musical passage. First, explicit memory from the rehearsal itself was unnecessary for accurate performance. Without any forewarning about its location within the rehearsal passage, participants were unlikely to memorize the “target” note sequence during the first music rehearsal; participant feedback confirmed that they had no explicit memory of the target sequence from this rehearsal. Knowing that one variant note at most would appear on any trial, participants quickly determined the correct note for each note position, provided that it fell within their perceptual span. Accurate test performance required knowledge of the correct notes, but this did not reflect memory acquired from the initial music rehearsal. Second, musical performance and eye movement patterns during the 20 rehearsals reported here was inconsistent with performance from memory. Performing a sequence of isometric notes from memory produces low internote variability in timing (standard deviations of 20-30 ms or less, Grieshaber & Carlsen, 1996) as well as eye movements that skip over

remembered notes (Goolsby, 1994b; Land & Furneaux, 1997). Neither was the case in this study. These observations indicate that performance on the perceptual task did not merely reflect the number of target notes that could be explicitly recalled from the most recent music rehearsal.

Changes in iconic memory (Coltheart, 1980, 1983; Gegenfurtner & Sperling, 1993; Sperling, 1960) also could not account for the results, as the perceptual span was unaffected by the presence or absence of a post-stimulus mask. Furthermore, the observed increase in perceptual span resulted from rehearsing the musical passage rather than the testing process itself; participants with 20 rehearsals before the first test session showed perceptual spans equal to those tested frequently before the twentieth rehearsal. The group of participants tested on multiple sessions showed higher accuracy at individual note positions without showing an increase in the overall perceptual span, indicating that the spatial range of perception is independent of the overall performance accuracy.

CHANGES IN SPATIAL PROCESSING

The perceptual span increased across rehearsals, indicating that the spatial range for perception was enlarged. Accuracy within the initial perceptual span varied little by note position; within the expanded perceptual span following rehearsals, accuracy decreased for later note positions (see Figure 3). Because gaze tended to be directed near the beginning of the sequence, these differences may reflect limited acuity in peripheral vision (Legge, Mansfield, & Chung, 2001).

Although participants could direct their eyes according to their own preference, the musical sequence in the tachistoscopic task always began at the left edge of the staff, providing an inherent bias towards this location. Eye tracking revealed that the perceptual span was initially narrow and centered near the direction of gaze, extending from two notes to the left of gaze to one note to the right (4 notes total). With more rehearsals, the perceptual span increased in size, with extensions to the perceptual span directed entirely to the right. Perception is similarly greater to the right of gaze for participants when reading text in a language that progresses left-to-right (as reviewed by Rayner, 1998), whereas perception is greater to the left of gaze when reading a language whose orthography is right-to-left (Pollatsek, Bolozy, Well, & Rayner, 1981). Our findings suggest that the perceptual span becomes asymmetric as familiarity increases for specific stimuli, and that participants direct their gaze and attention so as to maximize their perceptual span for the current task conditions.

Skill Group Differences

GROUP DIFFERENCES IN PERCEPTUAL SPAN

Three groups of musical skill were included in this study—11 highly skilled musicians, 10 less skilled musicians, and 3 musically-illiterate participants. The musically illiterate participants showed no improvement in perceptual span with visual review; indeed, those without prior experience reading musical notation failed to reliably distinguish between target and variant notes during any test session. Early differences in perceptual span between skilled and less skilled musicians were greater for the “easy” passage, which contained common musical sequences that would be more readily recognizable by skilled musicians. Initial differences in span were modest for music that was appropriately challenging for the musicians’ skill (4 notes for less skilled vs. 5 notes for skilled musicians).

For unfamiliar musical passages with common musical patterns, skilled musicians had an advantage in the perceptual span (seven notes) over less skilled musicians (four notes). Seeing further ahead, skilled musicians sightread these “easy” passages at a faster tempo than less skilled musicians.

GROUP DIFFERENCES IN RESPONSE ACCURACY

Accuracy at some note positions within the perceptual span differed between skilled and less skilled musicians (see Figure 3A, for example, at note positions 1-2 following 20 rehearsals). This may reflect group differences in the ability to utilize musical cues such as global contour or the size of the musical interval of the variant notes, a possibility supported by informal analyses of our data (not presented). These informal analyses indicated that group differences persisted or in some cases increased after 20 rehearsals, suggesting that even when no differences are evident in the spatial range of perception, musical skill affects the quality (or *reliability*) of perception for musical notation. This possibility merits further investigation. The results of our informal analyses must be considered preliminary since they were confounded by differences in the incidence of musical cues in variant sequences viewed by skilled vs. less skilled musicians (see Table 1).

EFFECTS OF EXPERTISE

Expertise increases the ability to *recognize* and *recall* a meaningful pattern (Barfield, 1997; Garland & Barry, 1991; Gobet & Simon, 1996; Halpern & Bower, 1982; Kalakoski, 2007; Kawamura, Suzuki, & Morikawa, 2007). Chess experts, for example, can quickly recognize and later recall the number of chess pieces by grouping individual items into meaningful “chunks”

(Gobet, 1998; Gobet & Clarkson, 2004; McGregor & Howes, 2002). Chunking can involve perceptual as well as mnemonic processes (Reingold et al., 2001). The observed effects of expertise in previous studies do not necessarily reflect an improvement in perceptual span, however, as the observed perceptual advantages could result from expert knowledge about where to attend, where to direct the eyes, or quicker identification of a pattern (Goldstone, 1998).

In our study, the enlargement of the perceptual span for a score persisted beyond the rehearsal itself. This may explain how expertise through extensive rehearsals improves perception for new *meaningful* (but not random) stimuli (Gobet & Simon, 1996; Reingold et al., 2001). Note groupings that become familiar through rehearsal often reappear in new music; the more experience a musician has rehearsing new music, the more likely a sightreading passage will contain familiar note sequences associated with a larger perceptual span. Consistent with this explanation, experience rehearsing a wide variety of music improves sightreading (Lehmann & Ericsson, 1996), particularly for difficult passages (Kopiez & Lee, 2006). Furthermore, sightreading ability is best correlated with measures of prior accompaniment experience (which involves rehearsals), better than the correlation with prior sightreading performance (which does not involve rehearsals) or with musical skill for performances from memory (Kopiez & Lee, 2006).

*Learning and the Perceptual Span:
Implications for Sightreading and Musical Performance*

The increase in perceptual span across rehearsals represents a form of perceptual learning. Perceptual learning can result in a lowered detection threshold (Maehara & Goryo, 2003), a lowered discrimination threshold (Ari-Even Roth, Amir, Alaluf, Buchsenspanner, & Kishon-Rabin, 2003; Demany & Semal, 2002; Lu, Chu, Doshier, & Lee, 2005; Maehara & Goryo, 2003), and the development of a unified percept from patterned stimuli (Little & Thulborn, 2005). Unlike these other forms of perceptual learning, rehearsal in this study incrementally increased the spatial region and number of items that could be effectively perceived.

What is the potential relevance of an improved perceptual span to musical performance, and when would improvement in the perceptual span have its greatest impact on performance? To address these questions, consider the process whereby performance skill for a musical passage is acquired. Skilled musical performance requires some foreknowledge of upcoming notes; the appropriate sequence of movements for keyboard

musicians depends on both the current finger position and forthcoming notes, and expressive nuances require awareness of the relationship of notes within musical structures such as phrases. Preview of upcoming notes can potentially improve musical performance until auditory, motor, or visual memory allows upcoming notes to be anticipated. In this study, changes in perceptual span for the score were acquired over 20 rehearsals. For most participants, performance at this point still showed high variability in internote timing; furthermore, gaze was directed to each note in the rehearsal passage, suggesting that performance was not yet guided from memory (Goolsby, 1994b; Land & Furneaux, 1997). Without memory, maximal performance speed during these 20 rehearsals may have been limited by the ability to rapidly *perceive* notes, consistent with the observed correlation between improvements in performance speed and improvements in perceptual span.

Later—as music becomes increasingly familiar—musicians eventually *remember* sequences of notes, at which point the musical notation becomes a cue for planning a *motor* sequence. At this point, many of the remembered notes are no longer fixated (Goolsby, 1994b; Land & Furneaux, 1997), presumably because perception of each note is unnecessary. Thus, enlarging the perceptual span may be most helpful for improving performance during early stages of music rehearsal, before note sequences have become memorized or well learned.

Although a larger perceptual span can provide better performance speed and musical performance, there may be practical reasons why it must be acquired through experience. A larger perceptual span requires additional information processing and storage within the brain; visual information processing for details is particularly challenging outside the 3° area of central vision (roughly corresponding to the original perceptual span evident here during sightreading). During music rehearsal, the rate of perceptual information that can be accessed is limited by the tempo and the time required for motor preparation—e.g., identifying which finger will move to perform the next note and the timing of its movement. A perceptual span that is larger than what can be accessed serves no functional purpose, wasting cognitive resources. As familiarity is gained through rehearsal, memory of the musical contour and the general pattern of finger movements allows motor preparation to begin earlier; motor preparation can then be facilitated by access to more perceptual information. The size of the perceptual span during rehearsal may thus adapt to accommodate what can be effectively used (Furneaux & Land, 1999).

*Learning and the Perceptual Span:
Broad Implications*

This study is the first to directly demonstrate an effect of music rehearsal on the perceptual span, and the first to demonstrate any type of rehearsal-related changes in the spatial range and number of perceived items within a single fixation. Musical expertise produces quicker recognition of music notation (Waters et al., 1997), and perceptual learning and expertise produce quicker pattern recognition and recall in other fields as well (Gobet & Waters, 2003; Goldstone, 1998). Although they reflect improved perceptual efficiency, these findings do not necessarily reflect a change in the spatial range or in the number of items perceived within a fixation, as experts may simply direct their eyes more quickly to important items or patterns and remember them better. Improved perception from familiarity also can be inferred from perceptual span studies on reading text, as highly familiar words are associated with a larger perceptual span within a single fixation (Henderson et al., 1995; Inhoff, 1989; Rayner, 1986a). However, the dual-route model of reading suggests that exception and high-frequency words are learned holistically, unlike the phonetic learning used to read less common words (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). By this account, perception of the familiar word is learned and perceived as a single item, which would not require an incremental increase in the perceptual span for its component letters.

The time course over which effects on perception develop with expertise has never been fully explored. Whereas conceptual expertise in an area must be acquired over many years, our findings indicate that perceptual effects of expertise can be acquired relatively rapidly, at least for the spatial extent of perception within a specific musical passage. Furthermore, the effects of 20 rehearsals on a challenging musical passage provided the same perceptual advantage for skilled experts and nonexperts alike.

Enlargement of the perceptual span for music within a single fixation reflects a form of perceptual learning. Other forms of perceptual learning may arise from local cortical interactions whereby the selectivity of a group of neurons is increased (Ghose, 2004; Schiltz et al., 1999; Skrandies, Jedynek, & Fahle, 2001). By contrast, the

perceptual learning demonstrated in this study must reflect functional reorganization of cortical interactions. Because visual space is mapped onto the cortical surface, information from additional areas of visual cortex must become accessible to perceptual processes as the perceptual span enlarges. This type of change in cortical interactions has been observed for language, where interactions between cortical language areas change according to the cognitive requirements of the task (Bitan et al., 2007). Identifying the learning-related changes in brain activity and connectivity associated with the demonstrated increase in perceptual span could help us understand how high-level cognitive processes during learning can modify our perceptions of the environment.

Although a few studies have shown that early and late learning processes involve activity in different brain areas (e.g., Little & Thulborn, 2005; Raichle et al., 1994; Walsh, Ashbridge, & Cowey, 1998), most studies and models treat learning as a single event. Learning in our study was *not* all or nothing, as the perceptual span increased incrementally; consequently, the size of the perceptual span provided an objective means to quantify how much learning had occurred. The changing size of the perceptual span following rehearsal could thus be used to study learning and its underlying brain mechanisms as a dynamic process.

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