

Interdependence of Right and Left Hands in Sight-read, Written, and Rehearsed Fingerings of Parallel Melodic Piano Music

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In an exploratory study of interactions between left hand (LH) and right hand (RH) fingerings, 6 professional pianists performed two Czerny studies in which LH and RH negotiate identical isochronous melodic material separated by one octave. Participants performed at sight and following rehearsal, with RH alone and hands together. Performances were recorded as MIDI data and as birds-eye video of the hands. Fingerings were transcribed from (slow motion) video recordings. Pianists wrote (optimal or intended) fingerings on scores during rehearsal. Intended LH fingerings were disrupted by hands-together performance more than intended RH fingerings, and RH fingerings involved more or bigger stretches between fingers than LH fingerings. Both findings are consistent with the intuition that pianists focus more attention on RH than LH fingerings in parallel melodic passages. Possible reasons include the difficulty of dividing attention between the hands, differences between the technical skill of the hands in fast melodic passages, and the greater perceptual salience of RH errors.

Passages in which the left and right hands (LH and RH) play in parallel at a distance of one octave (often referred to as *unison passages*) occur commonly in piano music. Examples extend from short virtuosic episodes of passage work in scales and arpeggios (prevalent, e.g., in the piano sonata and concerto repertoires) to entire pieces (such as the final movement of Chopin's Sonata Op. 35 in B-flat minor). In Schubert's *Trout Quintet* D. 667, for example, parallel melodic (unison) passages occur repeatedly in the piano part, in all four movements. Some jazz pianists (e.g., Oscar Peterson) are highly skilled at two-hand melodic improvisation at an interval of two octaves.

Parallel melodic passages pose a particularly difficult technical problem to pianists, for several reasons. First, in rehearsal where fingering has already been planned in advance, the pianist needs somehow to attend to both hands simultaneously, or to repeatedly switch attention from one hand to the other. The attention literature abounds in empirical evidence for the difficulty of attending to two simultaneous sources of information, particularly when the two sources are similar (see, e.g., Eysenck & Keane, 1990, pp. 111–112). McLeod (1977), for example, found that subjects performing a tracking task, who also responded to a tone-identification task either vocally or with the hand not involved in the tracking task, were more inaccurate in the tracking task when the response to the tone-identification was manual than when it was vocal. Conversely,

Shaffer (1981) showed that expert pianists playing rehearsed music were able to control the fine detail of timing control in the two hands with some degree of independence (see also Palmer, 1996), suggesting that divided attention to timing may be easier than divided attention to decision making (e.g., finger choice). There is evidence that people can learn to overcome these difficulties to varying degrees, but never completely. The simultaneous determination and monitoring of fingering in parallel melodic piano music is a good example of concurrent, similar tasks which — at some level — cannot be attended to simultaneously.

Second, in sight-reading or improvisation, the fingerings in the two hands must be determined not only simultaneously but also several notes in advance of execution (Sloboda, 1984; Sloboda, Clarke, Parncutt, & Raekallio, 1998). Forward planning of fingering, and especially of changes of hand position, is necessary to ensure that the pianist never “runs out of fingers”. In sight-reading, a pianist is unlikely to have time to work out fingerings for the two hands separately from first principles (e.g., using “rules” of the kind listed by Parncutt, Sloboda, Clarke, Raekallio, & Desain, 1997). Rather, it appears that pianists access a sizeable “cognitive library” of fingering patterns that have been acquired gradually over years of pianistic training. Sources include technical exercises (including scales and arpeggios), fingerings printed in scores, principles of fingering taught by teachers and read about in

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books, and fingerings worked out creatively by individual pianists for pieces in their repertoire (Clarke, Parncutt, Raekallio, & Sloboda, 1997).

Third, because the hands are mirror-symmetrical with respect to each other, different fingerings are required for the two hands. For example, where the RH plays the sequence CDEF with the fingering 1-2-3-4, the LH may play the same sequence 4-3-2-1; and where the RH plays CEDF 1-3-2-4, the LH might play 4-2-3-1.¹

Fourth, the asymmetric relationship between the hands, coupled with the desire to facilitate fingering in each hand separately, tends to lead to asynchronous changes of hand position,² which are difficult to coordinate. But if a pianist forces position changes to occur simultaneously, the technical difficulty will increase in one of the two hands when considered separately. According to Niemann (1967, p. 19) and Raekallio (1996, p. 228), this latter constraint is the lesser of two evils: both authors argue for simultaneous changes of hand position (including simultaneous use of the thumb) in parallel melodic passages, referring to examples from the piano literature. In the terminology of motor-control research, synchronous hand-position changes allow integration of timing mechanisms for the separate hands prior to movement execution; in such cases, the timing of bimanual movements can be more accurate than timing of corresponding movements in the separate hands (Helmuth & Ivry, 1996).

Returning to the pianistic literature, the question of which hand's fingering should be disrupted to accommodate synchronous changes of position is not clear. Pianist Garrick Ohlsson, for example, suggests that the LH should be louder than RH in unison (parallel melodic) passages: "In brilliant unison passages it is a cardinal principle for me that the lower voice vibrates much more — you almost don't need the right hand" (Elder, 1982, p. 171). This somewhat surprising assertion suggests allocating greater attention to the LH, and possibly even basing changes of hand position on LH fingering. In our experience — and, we assume, in the experience of most pianists — the opposite seems to be the case: the RH tends to lead the LH both in loudness and in the determination of fingering. The present study aimed to shed light on this issue. More generally, we aimed to make initial, exploratory progress in the systematic study of fingering in parallel melodic passages, focusing on interactions between the hands.

The piano repertoire chosen for this research was Czerny's *Kurze Übungen (Short Studies)* Op. 821, no. 54 in C-sharp major and no. 66 in G minor (Figure 1). The pieces were

selected according to the following criteria: the LH and RH play in parallel throughout, the pieces are not well-known by pianists, the pieces include a range of arpeggio- and scale-like configurations, and no widely agreed-upon fingerings exist for the pieces.³

Six pianists, none of whom knew the two pieces in advance of the study, performed them first at sight. Some months later, they were given the opportunity to rehearse the pieces, and performed them after rehearsal. Within each condition, they played each piece with RH alone and then with hands together. All performances were recorded both as birds-eye video of the hands and as MIDI data. Before the second, rehearsed session, the pianists also supplied their preferred fingerings for each piece in written form.

Hypotheses

On the basis of our musical intuitions and experience, together with results of structured interviews conducted with professional pianists (Clarke et al., 1997) and comments from the pianists participating in this experiment, we made the following predictions in advance of data analysis:

1. Similarity of fingerings. Fingerings written during rehearsal will be more similar to fingerings used after rehearsal than to fingerings used in sight-reading. Rationale: Pianists presumably use rehearsal time to approach their (written) fingering intentions.⁴

2. Synchrony of position changes. Changes of hand position will more often be synchronous (a) in sight-read than in rehearsed fingerings, and (b) in rehearsed than in written fingerings. Rationale: We assume that (a) asynchronous position changes are considerably more difficult than synchronous changes, and require considerably more rehearsal; and (b) written fingerings tend to be ergonomically optimal for LH and RH separately, necessitating asynchronous changes due to the asymmetry of the hands.

3. Interference between hands (a). Performed RH fingerings will be disrupted by the presence of the LH, that is, performed RH fingerings in the RH-alone condition will be different from performed RH fingerings in the hands-together condition. Rationale: Playing with hands together requires distribution of attentional resources between the hands.⁵

4. Interference between hands (b). When comparing fingerings observed in hands-together, rehearsed performance with

Figure 1
Scores of pieces from Czerny's *Kurze Übungen* Op. 821. (a) No. 54 in C# major. (b) No. 66 in G minor. © 1922 by C.F. Peters. © renewed 1948 by C.F. Peters. Reproduced by kind permission of Peters Edition Limited, London. The scores presented to experimental participants were as shown except that fingering and tempo indications had been deleted (by copying, applying correction fluid, and recopying).

fingerings previously written on the score, performance will cause more disruption to written LH fingerings than to written RH fingerings. Rationale: During performance, performers are more aware of fingering in the RH than in the LH. Possible reasons include the difficulty of dividing attention between the hands, differences between the technical skill of the hands in fast melodic passages, and the greater perceptual salience of RH errors.⁶

5. Relative difficulty of written, rehearsed, and sight-read fingerings. For both hands, written fingerings will be ergonomically easier than rehearsed, and rehearsed easier than sight-read. Rationale: It takes time to arrive at a good fingering when there are many different possible fingerings to choose among.⁷

6. Relative difficulty of LH and RH fingerings. In all conditions, RH fingerings will be ergonomically easier than LH fingerings. Rationale: It is difficult to attend to the fingerings of both hands at once. In parallel melodic motion, pianists may focus on RH and allow LH to follow.

METHOD

Participants

Six pianists were recruited by mail. Professional pianists who were not in full-time university employment were paid 25 pounds per hour; students, 10 pounds. All had university-level diplomas in piano performance. On average, they had played (practised and performed) regularly for 27 years ($SD = 13$ years). Three pianists had played for 30 to 50 years; the other three for 15 to 17 years. Two of the pianists were giving regular public performances (50–60 per year); the other four performed relatively seldom (0–5 per year). Four pianists of the pianists were right-handed, and two left-handed.

Materials

Each pianist played two pieces from Czerny's *Kurze Übungen* Op. 821: No. 54 in C-sharp major, and No. 66 in G minor⁸ (Figure 1). Each piece involved parallel melodic isochronous sixteenth-notes for 7.5 measures of 4/4 meter. In all, there were 121 notes in each hand. Pianists were given no fingering guidelines of any kind, whether verbally or in writing; no fingerings were visible on the experimental scores.

Procedure

The pianists performed on two separate occasions. On the first, they were shown the pieces for the first time and asked to sight-read them. Eight months later,⁹ during a session that involved other fingering tasks, they were sent scores of the pieces by mail a few days in advance of their performances, and asked to rehearse them privately. During rehearsal, they were asked to mark their preferred fingering on the score (i.e., to "finger" every note on the score). On both occasions, they first played the Study in C-sharp major with RH alone, then with hands together, then the Study in G minor RH alone, then with hands together. The order of pieces was not counterbalanced, because we were not directly interested in comparing the pieces with each other. Nor was the order of "handings" (separately then together) counterbalanced, because we wanted the task to be typical of rehearsal practice (and so ecologically valid). On both occasions, the pianists performed one or more different tasks at the keyboard before repeating all four performances. In all cases, they were free to choose an appropriate tempo.

Raw data

Performances were recorded as MIDI data and as birds-eye videos of the player's hands. Fingerings were transcribed by

student pianists enrolled at the Department of Music, Keele University, who were paid 10 pounds per hour. They watched the video in slow motion, typing fingerings directly into the MIDI files using specially designed software. In unclear cases such as errors (playing the wrong note, or failing to play a note), transcribers provided a fingering that they believed the pianist had intended for the note in question. Errors were located by ear and by eye¹⁰ and recorded directly into the MIDI files. The raw data for the study consisted of these MIDI files, and the fingerings written on the scores by the pianists.

Design

The design was limited to an initial exploration of interactions between LH and RH fingerings. The 6 pianists each played the two pieces in two different "handings" (RH alone then hands together), in two repetitions, and under two different conditions (sight-read and rehearsed). In all, there were 96 performances. For each combination of piece and condition, only the repetition with fewer note errors was fingered and analysed.¹¹ If the same number of note errors occurred in both repetitions, the second version was used. Our analysis is based on these 48 performances.

RESULTS

Tempo

No tempo indication appeared on the scores presented to the participants (Czerny's tempos and fingerings in Figure 1 had been deleted). We may safely assume, however, that all participants were aware that music of this kind is generally intended to be played fast. Few were able to play the pieces at a tempo close to that intended by the composer; in the sight-reading condition, only one pianist achieved such a tempo. The tempo of each performance was determined from the time interval in the MIDI file between the onset of the first note and the onset of the last. Large tempo variations were observed among the 6 pianists, from 350 ms per sixteenth-note (or 43 quarter-notes per minute) for the slowest sight-read performance to 140 ms per sixteenth note (or 117 quarter-notes per minute) for the fastest rehearsed performance. Rehearsed performances were generally played faster than sight-read, $F(1, 24) = 11, p < 0.005$; mean sixteenth-note durations were 230 ms (sight-read) and 180 ms (rehearsed).¹² In both cases, the tempo of performances with RH alone did not differ significantly from performances with hands together, $F(1, 24) = 0.00, p = 0.95$, in spite of the evident increase in cognitive load when playing hands together; the pianists seem to have tacitly regarded the maintenance of a constant tempo across these conditions as obligatory.

Three convergent pieces of evidence suggested that the two pieces were about equally difficult to learn. First, no significant difference was observed between the tempos of the two pieces. Second, for fingering difficulty values according to the stretch rule (see below), there was no interaction between piece and condition (sight-read vs. rehearsed). Third, there was no significant difference between the number of errors made in each piece.

Playing Intended Fingerings

Fingerings differed across the three conditions (sight-read, written, rehearsed: $F(2, 102) = 26, p < 0.001$).¹³ This was evaluated by counting the number of fingering differences between each pair of performances; the hypothetical maximum score was 121 (the number of notes in each performance). *Hypothesis 1* was confirmed: the smallest difference between any two of the three conditions was between written fingerings and fingerings in rehearsed performance. This difference averaged 15 notes, by comparison with 33 notes for sight-read versus rehearsed, and 36 notes for sight-read versus written.

Table 1
Minimum and Maximum Practical and Comfortable Spans (in Semitones) for All Pairs of RH Fingers in the Model of Parncutt et al. (1997)

| Fingers | MinPrac | MinComf | MaxComf | MaxPrac |
|---------|---------|---------|---------|---------|
| 1-2 | -5 | -3 | 8 | 10 |
| 1-3 | -4 | -2 | 10 | 12 |
| 1-4 | -3 | -1 | 12 | 14 |
| 1-5 | -1 | 1 | 13 | 15 |
| 2-3 | 1 | 1 | 3 | 5 |
| 2-4 | 1 | 1 | 5 | 7 |
| 2-5 | 2 | 2 | 8 | 10 |
| 3-4 | 1 | 1 | 2 | 4 |
| 3-5 | 1 | 1 | 5 | 7 |
| 4-5 | 1 | 1 | 3 | 5 |

Note. Leftmost column: for each entry fg , f is the finger number (thumb = 1, index = 2, etc.) of the first note, and g is the finger number of the second note. Positive entries in the body of the table represent rising intervals, negative falling. Because the pairs of finger numbers in the leftmost column are always increasing, and the table is for the RH, negative entries in the table refer to passing of the fingers over the thumb, or the thumb under the fingers.

The extent of fingering variations across the three conditions (sight-read, written, rehearsed) did not vary significantly with the two pieces or with three "handings" (RH alone, RH in hands together, LH in hands together).

Synchronicity of Changes of Hand Position

Parncutt et al. (1997) assigned difficulty to fingerings according to a system of rules. One of these, the *position-change-count rule*, states:

Assign 2 points for every full change of hand position and 1 point for every half change. A change of hand position occurs whenever the first and third notes in a consecutive group of three span an interval that is greater than the *maximum comfortable span* or less than the *minimum comfortable span* for the corresponding fingers. In a full change, three conditions are satisfied simultaneously: the finger on the second of the three notes is the thumb; the second pitch lies between the first and third pitches; and the interval between the first and third pitches is greater than the *maximum practical span* or less than the *minimum practical span*. All other changes are half changes (p. 353).

The *maximum comfortable span* may be thought of as the maximum span between a given pair of fingers without unavoidable tension due to stretching (see Table 1). It lies between the (bigger) maximum *practical span* and (smaller) maximum *relaxed span*. Most of the position changes necessary to perform the pieces under present consideration were half changes.

Applying this algorithm to fingered MIDI files, the mean number of synchronous hand-position (half-)changes per performance was 28, that is, 14 in the RH and 14 in the LH. This was considerably less than the number of asynchronous changes (49), of which more occurred in the RH (mean 26) than in the LH (mean 23), $T(57) = 2.25$, $p < 0.05$. In other words, RH positions contained slightly less notes, on average, than LH. *Hypothesis 2* was not supported: there was no significant variation in the number of synchronous changes between sight-read and rehearsed performances, or between rehearsed and written fingerings.

Interference Between Hands

Hypothesis 3 was not confirmed: Performed RH fingerings were not significantly affected by the presence of the LH. This negative finding is consistent with the idea that (much) more

attention is given to the RH. Given that some interaction between the hands is inevitable due to the inherent difficulty of divided attention, this suggests that, conversely, LH fingerings were substantially affected by the presence of the RH. Consistent with this expectation, the number of differences between written and rehearsed fingerings depended on hand, $F(2, 32) = 3.79$, $p < 0.05$.¹⁴ In the RH-alone performances, the difference averaged 11 notes; and in the hands-together performances, the difference for the RH was 13 notes, and for the LH, 21 notes. Thus, in the hands-together performances, the LH did not disrupt intended RH fingerings any more than they were already disrupted by the act of performing, but in hands-together performances, intended LH fingerings were disrupted more than intended RH fingerings, confirming *Hypothesis 4*. There are two possible explanations for this finding: either the act of performing hands-together disrupted intended LH fingerings more than intended RH fingerings, or pianists were less skilled at planning and writing LH fingerings in advance. In the absence of any evidence (anecdotal or otherwise) in favour of the latter, we assume the former.

Calculated Difficulty

The difficulty of a fingering can be broken down into ergonomic (anatomical/motor), cognitive, and interpretive aspects. According to Parncutt et al. (1997), ergonomic contributions to the difficulty of a fingering involve stretches between fingers, changes of hand position, use of weak fingers (4 and 5 in isolation, and specific successions of 3, 4, and 5); placing of 1 or 5 on a black key, or 4 on black when 3 is on white; and thumb-passing. Here, we calculate the difficulty of sight-read, written, and rehearsed fingerings of our pianists according to one of the more important of these ergonomic contributions: stretches.¹⁵

The *stretch rule* of Parncutt et al. (1997) is formulated as follows: "Assign 2 points for each semitone that an interval is greater than the *maximum comfortable span* or less than the *minimum comfortable span*" (p. 349). The values assumed for maximum and minimum comfortable and practical spans are also shown in Table 1.

The difficulty score accumulated by the stretch rule varied with piece, $F(1, 67) = 33$, $p < 0.001$; hand, $F(1, 67) = 22$, $p < 0.001$; and performance condition, $F(2, 67) = 6$, $p < 0.01$.¹⁶ The effect of piece is trivial: stretches occur at different places and in different ways in the two pieces (see Figure 1). Regarding performance condition, the greatest average stretch score occurred in the sight-reading condition (mean 52) and the smallest in rehearsed performance (mean 39) — not, as we expected, in written fingerings (47). *Hypothesis 5* was thus only partly confirmed in the case of stretches. This finding suggests that rehearsal allows pianists to gradually reduce the number of unnecessary stretches, even beyond the number required to execute their own written fingerings. Evidently, the determination and writing of fingerings is not a straightforward matter, even in studies of this kind. Repeated rehearsal is required to determine the best fingerings, and procedural knowledge ("trying it out at the keyboard") appears to play an essential role in this process.

Regarding the effect of hand, stretch scores for the RH (mean 54) far exceeded scores for the LH (38),¹⁷ suggesting that pianists were more likely to risk large stretches, or more often used stretches, in the RH than in the LH. This finding contradicts, and sheds new light on, *Hypothesis 6*, in the case of stretches. Two possible explanations exist: First, the pianists may have been focusing more visual and cognitive attention on the RH than the LH, taking more care about fingering decisions in the RH and assigning relatively few cognitive resources to the determination of LH fingerings — in short,

letting the LH follow the RH's lead.¹⁸ Another possible reason is that the pianist's RH is more skilled than the LH at playing fast melodic passages (cf. Brotz, 1992; Oldfield, 1969), due to different demands placed on it by the piano literature. Therefore, pianists are better able to handle technical difficulties in the RH, such as larger stretches.

DISCUSSION

In piano music where the hands move in parallel at an interval of one octave, we observed that (a) intended LH fingerings were disrupted by hands-together performance more than intended RH fingerings, and (b) RH fingerings involve more or bigger stretches between successive fingers than LH fingerings. Both these findings are consistent with the idea that pianists focus more attention on RH fingering than on LH fingering in this kind of music.

These effects appear to be a consequence of the impossibility of dividing or evenly sharing attention between the two hands. But it is not clear a priori which hand should receive more attention. Pianists might devote more attention to the LH to compensate for its lesser technical skill; this may be the reason underlying the comment by Ohlsson in the introduction. Pianists may devote more attention either to their dominant hand (because of its dominance) or to their nondominant hand (to compensate), but given the non-atypical ratio of righthanders to lefthanders (4:2) and small sample size of the present study, we cannot test how this might have affected the results. Our opinion, based on the present results and on our experience as pianists, is that more attention is allocated to the RH for the following two reasons. First, the RH may be the natural focus for attention due to its musical prominence. In multivoice music, the most prominent melodies tend to occur in the upper voice. Most music gives priority to the upper register in terms of melodic interest and activity; it is usually the upper line that carries what the listener would regard as the "tune". Listeners' acquaintance with this state of affairs (convention?) may mean that greater attention is paid to the upper voice in multipart music, including the two-part music used in the present study. Therefore, pianists need to be more careful about RH than LH performance. Second, errors in the RH may tend to be more perceptually salient, that is, more noticeable to listeners, than errors in the LH. Effects such as simultaneous and forward masking of complex sounds by other complex sounds, pitch salience as a function of register, the JND for pitch, and sensitivity to roughness in complex tonal contexts could cause errors in the pieces investigated here to be more perceptually salient in the upper than in the lower part. A simple perceptual experiment, in which listeners count the number of errors they hear in LH and RH, could clarify whether errors in the upper part are more salient, but would not necessarily shed light on the origin of the effect — historical, psychoacoustic, or a combination of both (e.g., psychoacoustic effects may be responsible for the historical emergence of the compositional convention of placing melodies mainly in the upper voice). Such an experiment could reveal a more complex situation: for example, the difference in salience of RH and LH errors may depend on pitch register. A further experiment that could be performed might involve the pianists playing the same pieces with hands crossed; but other confounds (the technical difficulty of playing cross-handed, which hand is over and which under, and so on) would interfere with the results, and in any case such a test would not be ecologically valid.

A problem with the design of the present experiment was that pianists first played RH alone and then hands together. This may have biased them towards a focus on the RH during the following hands-together condition, or made it easier for

them to use more challenging fingerings in the RH than in the hands-together condition. This design weakness means that the main findings must be treated with some caution. Future work should more carefully balance the roles of the two hands.

An issue that was neglected in the present study is that of timing between hands. It is well known that the member of a musical ensemble who carries the melody (e.g., the first violin in a string quartet) tends to anticipate tone onsets by some tens of milliseconds (Rasch, 1979). According to auditory stream segregation theory (Bregman, 1990), the perceptual purpose of this strategy may be to more clearly segregate the melody from its accompaniment. Palmer (1996) and Repp (1996) observed a similar effect in piano performance. In this case, however, there is an additional possible explanation: onset leads may be artefacts of the mechanics of the piano action. If two fingers strike the key surface simultaneously, but the keys are depressed with different velocities, the key that is depressed more quickly will reach the keybed first, so the louder tone will sound before the quieter one. Yet another possible explanation (not yet systematically investigated) is that pianists vary the timing of nominally simultaneous tones in order to manipulate the timbre of the resultant sonority. The situation is further complicated by the observation that some pianists deliberately *delay* melody tones relative to accompaniment tones, in certain musical styles. We did not analyse patterns of timing anticipation and delay between the hands in the present study, because it is not clear in advance what conclusions about fingering choice may be made from such data. This could, however, be an interesting field for future exploration.

A somewhat surprising finding was the lack of variation in the number of synchronous hand position changes between sight-read, rehearsed, and written fingerings (Hypothesis 2). One possible interpretation is that pianists took no notice of whether position changes were simultaneous. In other words, position-change synchronicity was random. It would be difficult to test this hypothesis statistically, given the various possible fingerings in each hand. Another possibility is that two different tendencies worked in opposition. On the one hand, one might expect changes of hand position to be more often synchronous in sight-read than in rehearsed fingerings, because synchronous changes are easier to perform than asynchronous changes; but on the other hand, pianists may deliberately adopt synchronous changes during rehearsal, because they facilitate fast playing. Further, one might expect synchronous changes to be more common in rehearsed than written fingerings, because written fingerings tend to be ergonomically optimal for LH and RH separately, and take no account of synchronicity; but it is also possible that pianists deliberately include synchronous changes in their written fingerings.

The preliminary results of this study, if confirmed by further work, may have practical implications for pianists and piano teachers. In conjunction with other literature on divided attention, our results suggest that the RH and LH should not, as is often tacitly assumed, be treated equally in parallel melodic passages. Instead, it may be technically, cognitively, and even musically optimal to allow one hand (probably the right) to lead and the other to follow, in such passages. Rather than striving to achieve the apparently impossible ideal of allocating equal attentional resources to the two hands, pianists might explicitly acknowledge, and take advantage of, a bias toward one of the two hands.

When determining the fingering for parallel melodic passages, we tentatively recommend the following approach. First, determine the fingering for the RH as if it were to play the passage alone. Then determine a LH fingering that fits well with the RH fingering already established. The LH fingering should involve as few stretches as possible, so that it can be

negotiated reliably while watching the RH, and as many synchronous changes with the RH as possible, to facilitate coordination.

Combining our findings with everyday musical considerations, we suggest the following three additional strategies. First, accents resulting from changes of hand position may either be minimised by avoiding stretches and difficult changes, especially in the LH, or used to musical advantage, by lining them up with metrical accents (downbeats) or structural accents (phrase beginnings). Second, if finger legato¹⁹ is required, a fingering should be chosen that allows legato to be maintained in one hand (probably the right) whenever it cannot be maintained in the other. Third, fingerings should not be finalised until a considerable amount of practice, and experimentation with different possibilities, has been done.

Many of these ideas are of course already familiar to pianists. Psychological research of the present kind may have the function of crystallising knowledge that is already intuitively available and allowing it to be applied more explicitly in musical practice.

Future research based on this initial, exploratory study may provide psychological as well as musical insights in the area of motor control. Virtuoso piano performance involves the training and execution of complex motor programs that approach the limits of human cognitive capacities (cf. Krampe & Ericsson, 1996; McKenzie, 1984; McKenzie, Nelson-Schutz, & Wills, 1983; Shaffer, 1981). Through coupling MIDI technology with video transcription of fingering, as we have done, or — better — by automatically recording fingering in real time (as planned by Parncutt, 1998), these processes will be increasingly available for empirical examination.

Footnotes

1. We number the fingers according to standard keyboard practice: 1 = thumb, 2 = index, ... and 5 = little finger. Italics distinguish finger numbers from other numbers in the text.
2. A change of hand position is a movement of the whole hand relative to the keyboard such that a different set of keys falls beneath the five fingers. It is often achieved by a pivotal motion relative to the laterally mobile thumb.
3. Individual pianists frequently choose quite different fingerings from those of the composer shown in Figure 1 (see Parncutt et al., 1997).
4. This hypothesis is not as trivial as it first appears. Other plausible principles or rationales lead to contrasting predictions. First, more spontaneous fingerings may be more similar to each other than to less spontaneous fingerings, because spontaneous fingerings draw more directly on a pianist's procedural knowledge ("overlearned" vocabulary of "automatic" or "subconscious" fingering routines). Second, rehearsed fingerings may not differ much from sight-read fingerings if the pianists practised less than they said they did (or not at all). Both these ideas lead to the counterhypothesis that sight-read fingerings will be more similar to rehearsed fingerings than either are to written fingerings.
5. Of course, the same would apply in reverse: LH fingerings should be disrupted by the presence of the RH. But that hypothesis was not tested in this initial, exploratory study.
6. Here, we assume that pianists can plan and write RH and LH fingerings with equal ease. In other words, we assume that written fingerings give an account of fingering intentions that is equally accurate for the two hands.
7. In recent work, we algorithmically generated hundreds of "playable" fingerings for melodic fragments taken from these pieces (Parncutt et al., 1997). We assume here that pianists try to find the ergonomically easiest fingering. This assumption is more likely to be valid for studies of this kind than for pieces from the artistic repertoire in which fingering can affect interpretation (see Clarke et al., 1997).
8. These two pieces were labelled "Piece D" and "Piece F" by Parncutt et al. (1997).
9. The relatively long time delay between experiments was intended to reduce the likelihood that the pianists would remember the pieces from the first session, and the fingerings that they used at that time.
10. Error counts were used only for the purpose of deciding which performances to analyse and which to abandon. Locating errors by ear

was deemed sufficient for this purpose. Presumably, many more errors were present in the MIDI files than were recorded by the transcribers.

11. We abandoned performances with more errors for the following three reasons. First, transcription is time-consuming and costly. Second, in the present study we were most interested in higher levels of performance expertise. Third, every error in a performance can lead to ambiguities in fingering.

12. This statistic is based on an ANOVA with total duration of performance as dependent variable (DV) and condition (2 levels: sight-read and rehearsed), piece (2 levels), and handing (2 levels: RH alone and hands together) as within-subject independent variables (IVs).

13. From an ANOVA with number of deviations in fingering between two performances as DV and piece (2 levels), comparison (3 levels: sight-read vs. written, rehearsed vs. written, sight-read vs. rehearsed), and handing (2) as within-subject IVs.

14. From an ANOVA with number of deviations in fingering between written and rehearsed fingerings as DV, and piece (2 levels) and handing (2) as within-subject IVs.

15. See above for predictions of difficulty caused by changes of hand position, given by the number of half changes plus twice the number of full changes.

16. From an ANOVA with difficulty according to stretch rule as DV, and piece (2 levels), condition (3), and hand (2) as within-subject IVs.

17. This difference is much greater than might result from differences in size between left and right hands. Differences in hand size were not measured in the present study, but typical data are available in Wagner (1988).

18. On the contrary, it could be argued that the bigger stretches in the RH are evidence that pianists were *less* careful in this hand, because that they were devoting *less* attention to it than to the LH. If this were the case, however, we would expect to see more errors in the RH than in the LH. In our experience as pianists, the number of RH errors in parallel passages tends to be less than the number of LH errors, due to the difference in technical skill of the two hands, or the greater perceptual salience of RH errors. We were unable to test this hypothesis in the present case, because our transcribers did not distinguish between the two hands while counting errors by ear.

19. *Legato* is the smooth joining of sound from one note to the next. In *finger legato*, the affect is achieved by depressing each successive key as, or just before, the preceding key is released. *Legato* may also be achieved using the pedal.

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