Journal of Motor Behavior, 2002, Vol. 34, No. 4, 339–351

On the Complexity of Classical Guitar Playing: Functional Adaptations to Task Constraints

Hank Heijink
Ruud G. J. Meulenbroek
Nijmegen Institute for Cognition and Information
University of Nijmegen

ABSTRACT. The authors performed a behavioral study of the complexity of left-hand finger movements in classical guitar playing. Six professional guitarists played movement sequences in a fixed tempo. Left-hand finger movements were recorded in 3 dimensions, and the guitar sound was recorded synchronously. Assuming that performers prefer to avoid extreme joint angles when moving, the authors hypothesized 3 complexity factors. The results showed differential effects of the complexity factors on the performance measures and on participants' judgments of complexity. The results demonstrated that keeping the joints in the middle of their range is an important principle in guitar playing, and players exploit the available tolerance in timing and placement of the left-hand fingers to control the acoustic output variability.

Key words: degrees of freedom, guitar fingering, music performance, skilled motor behavior

The movements that expert musicians have to perform in order to play a musical instrument properly are often unnatural, and they present an example of highly skilled, sophisticated task performance. The classical guitar ranks among the most demanding instruments in that respect. Complex passages frequently require the guitarist's hands to adopt extreme and awkward postures for very brief, strictly prescribed time intervals, which makes guitar playing both a spatially and a temporally demanding task.

Investigations of spatially or temporally demanding motor tasks have been mostly restricted to studies of the production of Morse codes (Klapp, 1995), tapping (see, e.g., Vorberg & Wing, 1996), typing (e.g., Rumelhart & Norman, 1982; Shaffer, 1978), or piano playing (e.g., Repp, 1999; Shaffer, Clarke, & Todd, 1985). Those studies have shown that the planning, execution, and monitoring of complex movement sequences involve the hierarchical control of a variety of cognitive and biomechanical processes. In the present study, we examined left-hand movements of professional classical guitar players to gain more insight into the biomechanical basis of the complexity of those movements. The cognitive and musical bases of complexity were not dealt with but are briefly addressed in the Discussion section. In the present article, we use the term *complexity* as a characteristic of a posture or a movement and reserve the term *difficulty* for judgments of how complex a posture or movement is, because there might be complex movements that the skilled performer considers easy and simple ones that he or she considers difficult to play.

The movements of the left and the right hands serve different functions in guitar performance. Whereas the performer uses the left-hand fingers to shorten the strings by pushing the strings on the metal frets (termed *stopping* a string), he or she uses the right-hand fingers to pluck the strings. The tone ranges of the guitar strings overlap, so almost every note of a musical score can be played on different strings. Furthermore, every note can be stopped with any of four fingers of the left hand (in classical guitar playing, the thumb is not used to stop the strings). The result of a performer's making a choice for a location and a finger for each note in a piece of music is called a *left-hand fingering*, or just *fingering.* In the notation system that is used for guitar music, fingerings are only partly, or not at all, prescribed, which makes selecting a fingering an important part of playing the classical guitar.

The total number of different fingerings grows exponentially with the number of notes in the piece: Even if a melody of n notes is played entirely on one string, the total number of fingerings is 4^n. An average guitar piece contains several hundred or even thousands of notes; so the total

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Correspondence address: Hank Heijink, NICI, University of Nijmegen, PO Box 9104, 6500 HE, Nijmegen, The Netherlands. E-mail address: heijink@nici.kun.nl

number of fingerings a guitarist can choose from for that piece is enormous.

The problem of finding a suitable left-hand fingering for a note sequence is closely related to the inverse kinematics problem that individuals continuously and effortlessly solve in everyday motor tasks such as pointing, reaching, and grasping (Rosenbaum, Loukopoulos, Meulenbroek, Vaughan, & Engelbrecht, 1995). In those tasks, people must select a suitable goal posture (i.e., a set of joint angles) from an infinite number of possible postures that, in principle, all allow successful task performance. In the case of guitar playing, that means that for a particular note, one of the four fingers needs to be allocated to a certain spatial position, given that many options are available. Like the inverse kinematics problem in other motor tasks, that problem is an instance of the more general degrees-of-freedom problem (Bernstein, 1967), which arises whenever there are multiple means to solve a task.

In motor control research, three solutions to that problem have been proposed (Rosenbaum, Meulenbroek, & Vaughan, 1996). In two of the solutions, the focus is on the role of joint coupling and intrinsic movement dynamics. In the third, to which we adhere here, redundancy is assumed to be controlled on the basis of cost containment. The problem of selecting optimal locations and fingers for every note in a sequence can indeed be seen as the planning of a low-cost series of postures that satisfy relevant task constraints (Rosenbaum et al., 1995; Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001).

Several principles concerning the basis on which costs might be contained have been advanced, such as the minimization of jerk (Flash & Hogan, 1985), torque change (Uno, Kawato, & Suzuki, 1989), muscle-tension change (Dornay, Uno, Kawato, & Suzuki, 1996), work (Soechting, Buneo, Herrmann, & Flanders, 1995), energy (Alexander, 1997), and neuromotor variance (Harris & Wolpert, 1998; Van Galen & Van Huygevoort, 2000). In the case of guitar playing, task goals are usually defined in terms of acoustic output, so cost containment might additionally be related to certain acoustic dimensions. However, because in the present study we focused on the biomechanical basis of the complexity of left-hand finger movements in guitar playing, we did not take the acoustic-output-related costs into account. Furthermore, because our study protocol did not allow us to assess the biophysical parameters listed earlier, we resorted to a more task-performance-related definition of movement cost, as proposed by Rosenbaum et al. (1995).

Following the theory of Rosenbaum et al. (1995) concerning multiple constraint satisfaction, we assumed that a guitarist is likely to choose the biomechanically easiest fingering when there are no other overriding cognitive or musical constraints to take into account. We assumed that in this study there would never be such constraints because the experimental task, that is, playing scales, is very simple in both cognitive and musical terms.

Apart from the work by Rosenbaum et al. (1995) and Rosenbaum et al. (2001) mentioned earlier, there is other support for the hypothesis that postures are adopted during task performance on the basis of a minimum-cost principle. Subjective ratings of postural comfort suggest that the cost of a posture is lowest when joints are in the middle of their range and increases nonlinearly when the joint angles leave the middle of their range (Cruse, Wischmeyer, Brüwer, Brockfeld, & Dress, 1990). Rosenbaum, Van Heugten, and Caldwell (1996) have provided further empirical evidence for that view by showing that oscillating the wrist around the axis of the forearm can be done more quickly when the forearm is in the middle of the pronation–supination range than when it is at either extreme (the so-called middle-is-faster effect). In guitar playing, there are many oscillating movements (e.g., trills), and being able to perform those kinds of movements fast is desirable; therefore, that could be the reason why guitarists prefer to keep their joints in the middle of their range.

In a pilot experiment in which we asked expert guitarists to rate the complexity of left-hand postures on the guitar, we were able to show that the findings of Cruse et al. (1990) also apply to guitar playing (Heijink, 1999). The complexity ratings were lowest when postures in the middle of the guitar neck were adopted and increased when the position on the neck was farther to the left or to the right. Furthermore, a large finger span was rated higher in complexity, that is, it was considered more difficult, than a small finger span. Because the hand's position on a guitar neck is strongly related to the shoulder and elbow joint angles and the finger span is related to the finger joint angles, the joint angles assumed in the postures might have determined the guitarists' complexity ratings. Consequently, hand position and finger span are likely determinants of the biomechanical complexity of left-hand finger movements in guitar playing.

For a sequence of only a few notes, those two factors might remain constant. With respect to transitions between postures that are required in longer note sequences, there are two types of postural transitions that are relevant. They concern transitions that require the hand to change position along the guitar neck and transitions that leave the hand in more or less the same place but require finger displacements. Those transition types are treated as separate entities in the pedagogical guitar literature (see also Baily, 1985; Sayegh, 1989). Repositioning the hand within a sequence of notes is considered complex because movements in guitar playing, as in any musical task, are time constrained, and the arm movement needed to reposition the hand is considered more complex than a finger movement is, given that both movements need to be performed in the same amount of time (Zelaznik, More, McCabe, & Thaman, 1988).

Indirect empirical support for that notion was obtained in a study by Rosenbaum, Slotta, Vaughan, and Plamondon (1991), who showed that the arm is best suited for large-amplitude and low-frequency movements, whereas the fingers are best suited for small-amplitude and high-frequency movements. Moreover, Meulenbroek, Rosenbaum, Thomassen, and Schomaker (1993) showed that in addition to the fact that limb segments have preferred movement amplitudes, frequencies, and directions, people display a tendency to continue using already-recruited limb segments. Changing a limb-segment pattern apparently is associated with an increase in movement costs.

In sum, we postulated that three biomechanical factors determine the complexity of left-hand finger movements in guitar playing: (a) the position of the hand on the guitar neck, where hand positions at either extreme of the guitar neck are presumed to be most complex; (b) finger span, where a large finger span is assumed to be complex; and (c) hand repositioning within note sequences. To examine those presumed complexity factors, we conducted a behavioral study in which we manipulated those three factors and evaluated the effects by means of kinematic analyses of the variability of expert guitarists' left-hand finger movements. Kinetic aspects also constitute important additional constraints in guitar playing, because the left-hand fingers must produce relatively large forces in order to press the guitar strings on the metal frets (for a discussion of kinetic aspects of tapping, cf. Sternad, Dean, & Newell, 2000), but those aspects were excluded from our analyses and are referred to in the Discussion. Effects of the complexity factors on the timing of the musical output and complexity ratings by expert guitar players were also assessed.

Concerning left-hand finger movements, we assumed that guitarists generally seek to minimize both spatial and temporal variability. Spatial variability must be contained because the target areas in guitar playing are relatively small. The distance between two frets (the *interfret space*) ranges from 12.9 to 36.5 mm on a classical guitar. Moreover, if the finger is placed too far to the left (away from the soundhole) in that space, the string will buzz against the fret when it is plucked; and if the finger is placed too far to the right (i.e., on the fret), the string's oscillations will be damped by the finger. Temporal variability must also be minimized because a composer prescribes a certain rhythm from which the guitarist cannot deviate too much if that rhythm is to be perceived correctly by a listener (see, e.g., Schulze, 1989).

In guitar playing, timing is controlled by both hands: The left-hand finger must be put down on the string before the right hand finger plucks it and produces the sound. That feature enabled us to analyze two temporal variables, the timing of tone production and the timing of left-hand finger placement, and one spatial variable, the position of the left-hand fingers in the interfret spaces. We expected that experienced guitarists who had been trained in the Western classical tradition would exhibit a high degree of control over the acoustic output of their playing, because music in the Western classical tradition is purely sound oriented, as opposed to, for example, African music, which is movement oriented (Baily, 1985). The timing and placement of the left-hand fingers offer much more freedom to the performer, however, so we expected an increase in complexity to become apparent in those measures. In particular, we expected that an increase in task complexity would increase the asynchrony between left-hand timing and the timing of tone production, analogous to complexity effects on movement latency in a variety of contexts (see Henry & Rogers, 1960; Klapp, 1980; Meulenbroek & Van Galen, 1988).

We expected that the effect of the hand-position factor on finger placement would be that in higher positions (i.e., positions closer to the soundhole), the fingers would be placed closer to the frets, because the interfret spaces become progressively smaller in higher positions, whereas the strings are progressively higher above the frets. For those two reasons, the tolerance in finger placement is smaller in the high positions. We expected that the hand-repositioning factor would increase the variability of the placement of the left-hand fingers after the hand repositioning, but we were uncertain whether hand repositioning would have an effect on the placement of the fingers before the actual repositioning. We also expected that an increase in finger span would cause the guitarists to place the fingers farther from the frets so that they could keep the finger joints closer to the middle of their ranges (Cruse et al., 1990; Rosenbaum et al., 1996).

Method

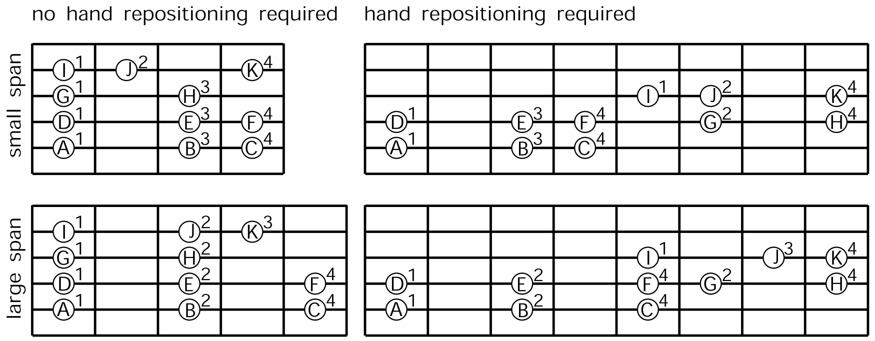
Participants

Six male professional classical guitarists whose ages ranged from 22 to 36 years participated in this experiment. They were all graduates of the Brabants Conservatorium in The Netherlands, and they were active performers and teachers. They were paid 100 Dutch guilders (approximately $39 U.S.) plus travel expenses for their participation. We asked professional guitarists rather than novices to participate in the experiment to avoid possible confounding effects of being in the process of learning to play the guitar.

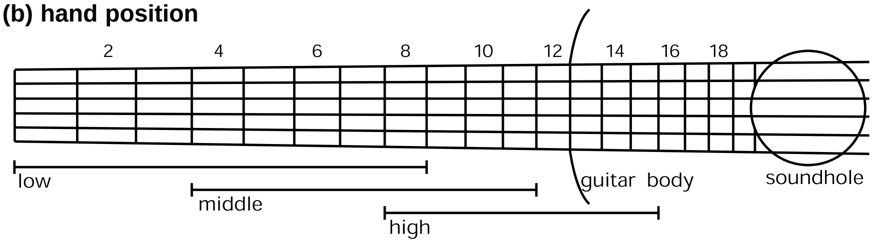
Stimuli and Design

For the sake of simplicity, we limited our study of left-hand fingering to sequences of single notes. We use the term *note sequence* in this article to denote a sequence of notated pitches without reference to positions on a guitar, whereas the term *finger-position sequence* is used for a note sequence to which a fingering is attached. We used musical scales as a basis for the stimuli. Scales are the building blocks of a large part of Western music, and musicians use them to practice their motor skills. As such, scales are overlearned patterns, in both the acoustic and the motor domains. A scale consists of 7 notes, but we extended the scale upward so that the note sequences became 11 notes in length.

In the top left of Figure 1a, the fingering pattern of the scale we used as a basis is depicted; the span between the index finger and the little finger was four frets. In the bottom left part of Figure 1a is the prescribed fingering that required a finger span covering five frets. The two finger-



(a) hand repositioning and finger span



(b) hand position

FIGURE 1. Prescribed left-hand finger-position sequences in which the complexity factors were varied. (**a**) Finger span was small (four frets) or large (five frets), and hand repositioning was or was not required. (**b**) Hand position was specified as the location of Note A, which was at the first fret (low position), fourth fret (middle position), or eighth fret (high position). The black lines show the range of the fingering sequences when hand repositioning was required. The diagrams of the guitar fretboard are shown as if a guitarist were looking down over the fretboard of the guitar; so, top and bottom are reversed, but left and right are respected. That is the standard way of showing, for example, a chord diagram.

ings shown in the left panels of Figure 1a did not require a repositioning of the hand. Their counterparts that did require a hand repositioning are shown in the right panels of Figure 1a . Note that for each level of the finger-span factor, Locations A through F were identical in both levels of the hand-repositioning factor. The hand repositioning had to occur somewhere between Locations F and G, because F is played with the little finger and G with the middle finger, and Location G lies to the right of F.

The four different fingering patterns shown in Figure 1a were shifted to different positions on the guitar neck such that the first note of the fingering was placed on Fret 1, Fret 4, or Fret 8 (see Figure 1[b] and Note 1). In that way, the patterns had to be played on the low, middle, and high parts of the guitar neck, respectively.

The participants were instructed to play the stimuli at a tempo of 5 notes/s. The tempo was maintained by a metronome ticking at 2.5 notes/s or 150 beats/min, so for every single metronome tick, 2 notes had to be played. A metronome tempo of 5 notes/s or 300 beats/min was considered too high to serve as a timekeeper.

The combinations of the finger span (two levels), the hand-repositioning (two levels), and the hand-position (two levels) factors led to 12 different finger-position sequences, and the guitarists played 12 consecutive replications of each finger-position sequence. The stimuli were presented in four blocks. Within each block, finger span and hand repositioning were held constant, whereas hand position was varied within each block. Hand position was counterbalanced within blocks, and the order of the blocks was counterbalanced over participants. In sum, the guitarists played 144 trials in four blocks of 3 different finger-position sequences in which each finger-position sequence was repeated 12 times.

Apparatus and Data Collection

Participants were seated on a piano bench that was adjustable in height. For ergonomic reasons, the classical guitar is normally held at approximately a 45° angle relative to the horizontal. All the participants played the same standard classical guitar; none of them had played that particular instrument before, but that did not present them with any problems.

The stimuli were presented in music notation annotated with fingering information on a 17-in., 1,024- × 768-pixel computer screen, at a distance of approximately 1.5 m from the participant, directly in front and below eye level, and at the height where the participants were used to having a sheet music stand. The guitar sound was recorded with a directional microphone placed close to the guitar.

A digital metronome (Yamaha YM-2000) was placed directly behind the computer screen, out of sight of the participants but clearly audible in the whole room. A second directional microphone recorded the metronome ticks. The sounds of the guitar and the metronome were recorded with a sampling frequency of 9 kHz.

We recorded the movements of the fingers of the left hand with a three-dimensional motion tracking system (Optotrak 3020, Northern Digital, Waterloo, Ontario). We used 10 infrared-light-emitting diodes (IREDs) for that purpose. Four IREDs were taped to the fingernails of the left hand, 1 on each nail; we tilted the IREDs back a few degrees to avoid obstruction of the camera view by the fingers and collisions with the guitar strings. One IRED was fixed to the back of the left hand, 2 were taped to the proximal phalanges of the index and middle fingers of the right hand, and 3 were fixed to the body of the guitar. The IREDs on the guitar provided a dynamic frame that we used to record the position of the fingers relative to the plane of the guitar fretboard; the IREDs on the right hand were used as a check on whether the prescribed right-hand fingering was followed throughout. IRED displacements were recorded with a frequency of 100 Hz and a spatial accuracy of less than 0.2 mm in each dimension. The IRED recordings were synchronized to the recorded audio signals of the guitar and the metronome.

Procedure

The participants were instructed to play the stimulus that was presented on the screen while observing the prescribed left- and right-hand fingerings and the metronome tempo. After the recording had been started, they could begin playing on any tick of the metronome. The duration of the playing session was approximately 30 min. Before each trial, the participants indicated that they were ready to start playing, and the experimenter started the recording. Subsequently, a green dot was displayed on the computer screen below the stimulus, informing the participant that he could start playing. After the whole stimulus was played, the experimenter stopped the recording and the green dot disappeared. The same procedure was repeated for each of the 12 replications.

Before playing each new finger-position sequence, the participants were allowed to practice the sequence as long as they wished (usually less than 1 min). After one block of three sequences, the participants took a short break (approximately 3 min); after six sequences, a longer break (approximately 15 min) was taken; and after nine sequences, the participants took another short break.

Pre- and Posttests

Before the main experiment, the participants were given a pretest in which they were given a printed sheet of the stimuli that had no fingering annotations. They were asked to write down the easiest fingering, without using a guitar; to do so, they had to rely on their ideas about biomechanical complexity instead of their ability to feel how complex a fingering is. We included that test because we suspected that biomechanical complexity would not be the only important factor in the task. The pretest consisted of 6 stimuli instead of 12 because the note sequences were identical in both levels of the hand-repositioning factor, although the fingering sequences were different (see Figure 1a). After the experiment, the participants were asked to rate on a 5-point scale the difficulty of the 12 conditions with the fingering annotations that were used in the main experiment. The pretest took approximately 20 min, the posttest approximately 10 min. The duration of the whole experiment, including pretest, posttest, and breaks, was approximately 2 hr.

Data Analysis

In the main experiment, we used a metronome to force the participants to play at a fixed tempo. Consequently, we were able to analyze, for each note, the timing of two behavioral events: (a) right-hand tone production and (b) left-hand finger placement. We also analyzed the spatial position of the left-hand fingers at the moment of tone production. Right-hand asynchrony was defined as the interval (in milliseconds) between the moment at which the metronome tick sounded and the moment at which the corresponding tone was produced. A negative right-hand asynchrony represented the situation in which the tone was produced too soon, that is, before the metronome tick, and a positive asynchrony implied that the tone was produced too late, that is, after the metronome tick had already sounded. Because the participants played two notes for every metronome tick, every second note had to be compared with an interpolated metronome tick. The ticks were interpolated so that they were exactly halfway between the two surrounding real ticks. Left-hand asynchrony was defined as the interval (in milliseconds) between tone production and the moment at which the corresponding left-hand finger was placed on the guitar neck. Because in guitar playing, left-hand finger placement always precedes the production of the corresponding tone, we expected only negative left-hand asynchrony values. In the spatial domain, left-hand finger placement was defined as the distance (in millimeters) between the position of the finger on the guitar neck at the moment of tone production and the position of the fret closest to that finger at the side of the soundhole. Because the finger is placed to the left of the fret, only negative values were expected.

The onsets of the tones in the guitar audio signal were automatically detected with a custom-written peak-detection algorithm. A peak was considered indicative of an onset if the difference between the maximum and the preceding minimum was higher than a threshold value. We determined the threshold by trying different values until the results of the algorithm, when applied to the first participant's data, were such that the number of detected onsets was between 10 and 12. The onset was defined as the point between local minimum and maximum where the second derivative was maxi-

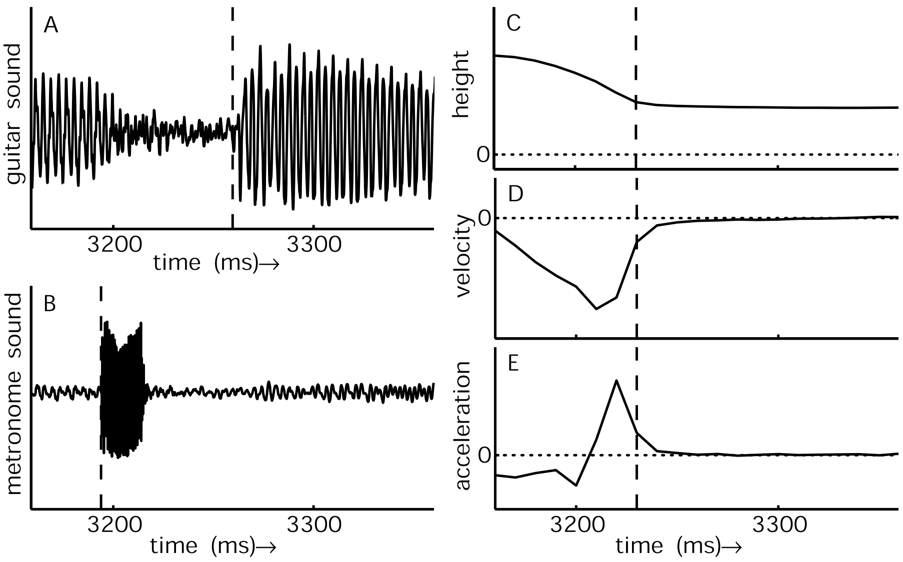


FIGURE 2. Example of data analysis, showing the output of the onset-detection algorithm as a dashed line on the acoustic output signal of the guitar (**A**), the output of the same algorithm on the metronome signal (**B**), and the impact detection of the left-hand finger placement: (**C**) is the position of the finger, (**D**) the velocity, and (**E**) the acceleration. The metronome and the guitar signals were sampled at 9 kHz and the movement signals at 100 Hz.

mal. The results of that algorithm were visually inspected and, if needed, corrected by hand (see Figure 2A). We filtered the metronome signal with a high-pass, zero phase-lag, third-order Butterworth filter with a 3-kHz cutoff frequency. With the onset-detection algorithm mentioned earlier (Figure 2B), we automatically detected the metronome ticks in the filtered signal. By analyzing the position–time functions of the fingers representing the finger movements perpendicular to the plane of the fretboard of the guitar, we detected the impacts of the left-hand fingers. An impact was defined as that point in time, between a maximum and a minimum in the position–time curve (Figure 2C), after a minimum in velocity (Figure 2D), where the acceleration was half of its local maximum (Figure 2E). Left-hand finger placements were defined as the *x* positions of the fingers at the exact time of tone production. All analyses were carried out in Matlab Version 5.2.1 for the Macintosh.

The mean and the standard deviation over replications were analyzed for every variable. We considered an increase in the variability as an indication of a decrease in performance caused by increased task complexity. Caution is needed with respect to that research strategy, however, because Slifkin and Newell (1998) have recently questioned the validity of that view. They argued that an increase in performance variability might reflect a freer use of the available degrees of freedom because of a decrease in task complexity. Consequently, we decided to use the pattern of the means in combination with variability to assess complexity effects. It should be noted, however, that temporal variability in tone production is undesirable and thus does not seem to be a candidate for that type of strategy.

We limited our analyses to the first six notes because only Notes A through F were comparable across all conditions (see Figure 1 and Note 2). In left-hand finger timing, we ignored the first note because, for that note, the participants placed the relevant finger on the required location before the recording was started, that is, long before the first tone was to be produced.

Using a mixed-model approach, we evaluated the means and standard deviations of the three performance measures by means of six separate analyses of variance (ANOVAs). There were four within-subject variables: hand position (three levels), hand repositioning (two levels), finger span (two levels), and note number (six levels; five in the case of left-hand asynchrony). When ANOVA results are reported in the present article, the mean square error terms (*MSE*) of the relevant *F* tests are also specified as an index of the between-participants variability that was present in the data. Our reason for reporting the *F* tests' *MSE* values is to show that the between-participants variability was small; that finding revealed that the participant group was homogeneous and allowed for the averaging of the data across participants. Post hoc comparisons of means consisted of Newman–Keuls tests with a critical *p* value of .05, or Student's *t* tests when appropriate. The statistics were computed in SPSS Version 10 and in JMP Version 4.0.2 for the Macintosh.

Results

Effects of Task Variables on Right-Hand Asynchrony

In Figure 3 are shown the effects of the task variables on the extent to which the tones that were played coincided with the metronome ticks. The left, middle, and right pan-

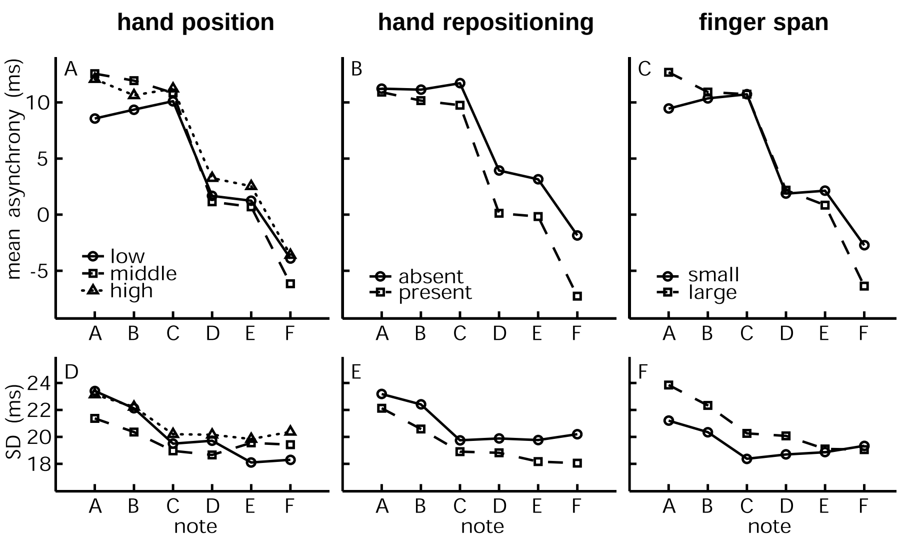


FIGURE 3. Effects of the complexity factors on right-hand asynchrony with respect to the metronome. The top panels (**A**, **B**, and **C**) show the mean asynchrony over replications; the bottom panels (**D**, **E**, and **F**) show the standard deviation, both in milliseconds. The letters assigned to notes correspond to the ones used in Figure 1(a).

els show the effects of the variations in left-hand position, hand repositioning, and finger span, respectively. In the top panels of Figure 3 are shown the mean right-hand asynchrony, and in the bottom panels, the variability in the acoustic output domain.

One can see from Figure 3 that the guitarists performed the task with high temporal precision. The mean ranged between –8 and +13 ms, which corresponds to a proportional timing error of only –4% to 6.5% relative to the 200-ms interonset interval of the notes. Timing variability was larger, however. It ranged between 18 and 24 ms (9% and 12% of 200 ms), as is shown in the bottom panels of Figure 3. The reason for that finding is that the participants showed very similar timing patterns across replications, but the whole pattern shifted forward and backward in time over replications. When the patterns were averaged over replications, however, participants were found to compensate for the shift of the pattern so that the mean was almost perfectly on the metronome; for that reason, the mean asynchrony was relatively small.

In the fragment that was analyzed, we found a significant effect of note number, $F(5, 25) = 5.97$, $MSE = 515$, $p < .001$. Participants played Notes A, B, and C after the metronome tick, Notes D and E more or less on the tick, and Note F before the tick. A post hoc Newman–Keuls test showed that the six notes could indeed be grouped into Notes A, B, and C; Notes D and E; and Note F. The tendency toward a negative asynchrony corresponded with the well-known phenomenon observed in tapping—that people also tend to progressively produce their tapping movements before pacing signals as the tapping sequence progresses (see, e.g., Vos, Mates, & Van Kruysbergen, 1995). A *t* test comparing the timing variability of notes on real metronome ticks with the variability of notes on interpolated metronome ticks showed that the variability of the right-hand asynchrony was not influenced by the 2:1 ratio of the frequencies of tone production and metronome ticks.

There were no significant main effects of hand position, hand repositioning, or finger span on either the mean or the standard deviation. Hand position significantly interacted with note number, $F(10, 50) = 2.18$, $MSE = 16$, $p < .05$, as can be seen in Figure 3A. The downward trend was more pronounced in the middle and high positions than in the low position. Hand position did not differentially affect the variability of the tone production.

As shown in Figure 3B, the interaction between hand repositioning and note number on the mean right-hand asynchrony, $F(5, 25) = 3.42$, $MSE = 19$, $p < .05$, indicated that the tendency toward more negative asynchrony was more prominent when a hand repositioning was required. A similar interaction occurred between finger span and note number, $F(5, 25) = 3.91$, $MSE = 24$ ms, $p < .01$.

Effects of Task Variables on Left-Hand Asynchrony

The effects of the task variables on the asynchrony between left-hand finger placements and the timing of tone production are shown in Figure 4. The organization of Figures 3 and 4 is the same. As expected, left-hand timing was always negative because in performing music on string instruments, the left-hand finger placements of right-handed musicians must precede their right-hand fingers' tone production. In all the panels in Figure 4, the tim-

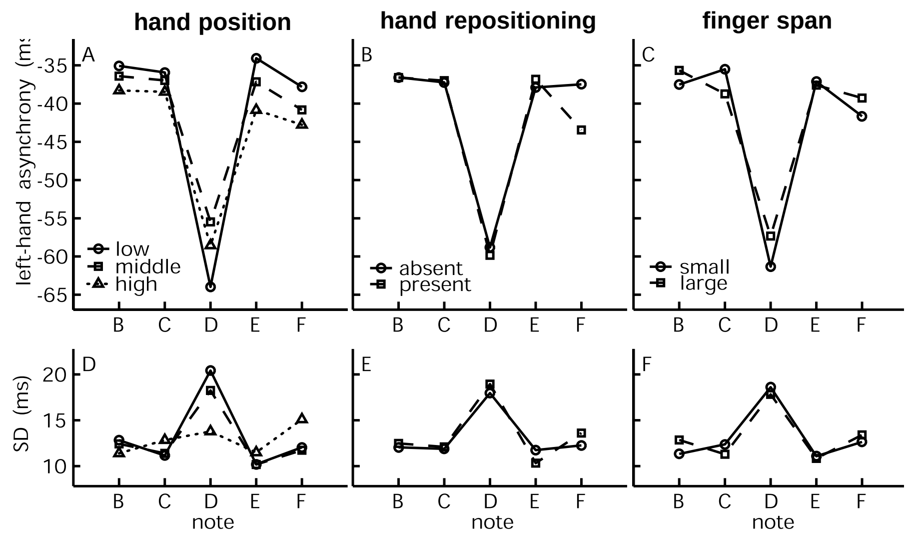


FIGURE 4. Effects of the complexity factors on left-hand asynchrony with respect to right-hand timing. The top panels (**A**, **B**, and **C**) show the mean timing, and the bottom panels (**D**, **E**, and **F**) show the standard deviation, both in milliseconds. The letters assigned to notes correspond to the ones used in Figure 1(a).

ing of the finger placement related to the sound of Note D stands out as compared with the timing of the finger placements related to the sounds of Notes B, C, E, and F. The finger that stopped Note D was placed on the string earlier than the fingers that stopped the other notes. We confirmed that finding by performing a post hoc Newman–Keuls test. Among Notes A through F, only Note D required the guitarist to switch from one guitar string to the next (see Figure 1a).

In Figures 4A and D, one can see that hand position and note number interacted significantly on both the mean and the variability of left-hand asynchrony, $F(8, 40) = 2.36$, $MSE = 78$, $p < .05$, and $F(8, 40) = 4.43$, $MSE = 13$, $p < .01$, respectively. Student's *t* tests revealed that on Notes B, C, E, and F, the means for the high position were significantly more negative than the means for the low position, whereas all the other means were not significantly different from each other.

A complementary effect can be seen on the variability of left-hand asynchrony (Figure 4D). On Note D, the variability was largest, particularly in the low position. Post hoc Student's *t* tests showed that the difference in variability on Note D was significant only for the low and the high hand positions.

Neither the hand-repositioning factor nor the finger-span factor had significant effects on left-hand asynchrony, nor did they have any effects on the variability of left-hand timing.

Effects of Task Variables on Left-Hand Finger Placement

The effects of the task variables on the position of the left-hand fingers in terms of the distance (in millimeters) between the fingers and the fret closest to the finger in the direction of the guitar's soundhole are shown in Figure 5. The organization is the same in Figure 5 as in Figures 3 and 4.

The left-hand finger placement data showed that the index finger (which was used to play Note A; see Figure 2) was placed farthest from the fret, the little finger (used for Notes C and F) was placed closest to the fret, and the middle finger or the ring finger (used for Notes B and E, depending on the finger-span condition) was placed in positions between those of the index and little fingers. In the characteristic guitar-playing hand posture, the index finger is oriented under an angle of approximately 45° with respect to the fretboard in the direction of the soundhole. As compared with the other fingers, the player must place the index finger farther from the fret in order to avoid damping the string. The little finger can be placed very close to the fret because it is almost perpendicularly placed on the fretboard.

Hand position had a significant main effect on the mean distance between the position of the left-hand finger and the position of the frets, $F(2, 10) = 25.10$, $MSE = 23$, $p < .001$. As the left hand's position was varied between low, middle, and high positions on the fretboard, the fingers were placed progressively closer to the frets (Figure 5A), which confirmed our predictions regarding that effect. There was a significant main effect of hand repositioning on left-hand finger placement, $F(1, 5) = 8.40$, $MSE = 3.1$, $p < .05$. The fingers were placed closer to the frets when a hand repositioning was not required than when it was required, as is shown in Figure 5B. Note D was an exception to that phenomenon: On that note, the finger was placed closest to the fret when a hand repositioning was required.

The finger span factor also showed a significant main

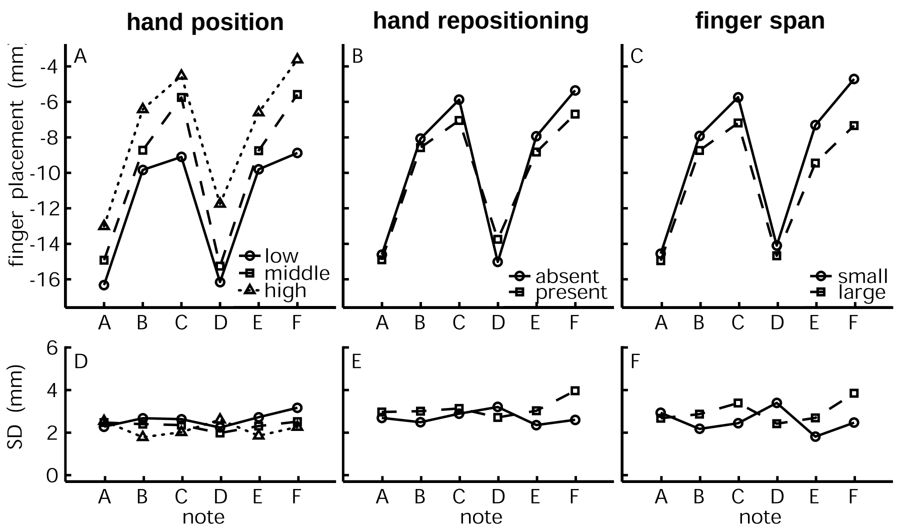


FIGURE 5. Effects of the complexity factors on left-hand finger placement with respect to the frets. The top panels (**A**, **B**, and **C**) show the mean placements, and the bottom panels (**D**, **E**, and **F**) show standard deviation, both in millimeters. The letters assigned to notes correspond to the ones used in Figure 1(a).

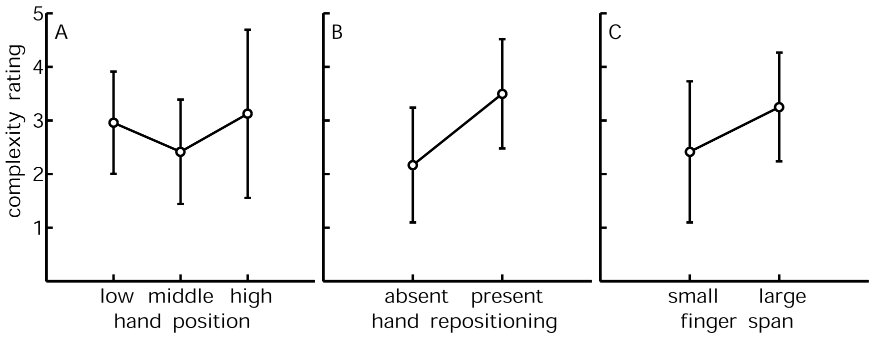


FIGURE 6. The participants' ratings about the complexity of the finger-position sequences used in the experiment. Means and standard deviation bars are shown.

effect on the placement of the finger in the frets, $F(1, 5) = 18.86$, $MSE = 10.2$, $p < .01$. The fingers were placed closer to the frets when the finger span was small than when the finger span was large (see Figure 5C). There were no other significant main effects of the complexity factors on the variability of left-hand finger placement.

Pre- and Posttests

The participants generated 31 different finger-position sequences for six different note sequences. When analyzed according to the experimental variables, the finger-position sequences required repositioning of the hand in only 2 of the 31 cases, showing participants' strong preference for avoiding that complex option. Moreover, in those cases requiring a hand-position change, the hand had to be moved only a single fret. With respect to hand position, our prediction was only partially confirmed. We expected that the middle of the guitar neck would be the preferred position, but the guitarists generated 17 fingerings in low hand positions (i.e., with the index finger below the fourth fret), 13 in the middle of the guitar neck (fourth to seventh fret), and only 1 case in a high position (higher than the seventh fret). Except for 1 fingering requiring a finger span of three frets and 1 requiring a finger span of five frets, all fingerings required a finger span of four frets.

The results of the posttest, in which the participants rated the complexity of the finger-position sequences that were used in the main experiment, indicated that the complexity factors played an important role in what they considered difficult sequences. We analyzed the data that are summarized in Figure 6 with a chi-square test, with the ratings as the dependent variable. Hand repositioning had the strongest effect on the participants' judgments, $\chi^2(2, N = 72) = 34.85$, $p < .0001$. The finger-span factor had the second most important effect, $\chi^2(1, N = 72) = 19.41$, $p < .0001$, and the hand-position factor the smallest effect, $\chi^2(1, N = 72) = 11.57$, $p < .005$. In sum, our hypotheses about the relative importance of the complexity factors were confirmed by the results of the posttest.

Discussion

Our main objective in the present study was to explore the biomechanical basis of the complexity of left-hand finger movements in guitar playing. On the basis of a detailed task analysis, notions on postural comfort (Rosenbaum et al., 1995; Rosenbaum et al., 2001), and the presumed advantages of keeping joints near the middle of their range of motion when performing complex motor tasks (Rosenbaum et al., 1996) or when assuming a complex posture (Cruse et al., 1990; Heijink, 1999), we posited three complexity factors, namely, the position of the hand on the guitar neck, the need to reposition the hand within a tone sequence, and the required finger span. To examine how 6 expert guitar players functionally adapted to variations in those task constraints, we asked them to perform simple 11-note scales under metronome-paced conditions. The finger-position sequences the participants indicated as preferred fingerings before the experiment, the acoustic output constancy of their performance while playing the prescribed fingerings, the temporal and spatial features of their left-hand finger movements, and, finally, their complexity ratings of the played finger-position sequences after the experiment yielded a coherent pattern of results that confirmed our notions of the biomechanical basis of complexity in guitar playing. To refine that claim, we evaluated the effects of the complexity factors on each of the assessed performance measures of the main experiment. First, however, we discuss the results of the pre- and posttests. As indicated in the introductory comments, nonbiomechanical aspects such as cognitive and musical factors that might have codetermined task complexity have been added to the discussion where relevant.

The results of the pretest showed that, when asked to provide the easiest fingering for a short note sequence, the participants avoided, as expected, large finger spans and hand repositioning. Contrary to our expectations, however, low hand positions (on the left side of the guitar neck) were preferred over middle hand positions in the pretest. The preference for low hand positions might have resulted from the fact that those are generally the most familiar positions on a guitar. Furthermore, in terms of redundancy control, when the hand is in the low position the need to explore alternative locations to the left of that position is eliminated because the guitar neck ends there. That finding indicates that nonbiomechanical factors might also have influenced the choice of fingering. The results of the posttest were in line with those obtained in the pretest. Having to reposition the hand was clearly thought to be difficult, as was a large finger span. Furthermore, expert guitar players consider a high hand position more difficult than a low or a middle hand position. Again, however, low and middle hand positions were judged equally difficult, probably for the two reasons just mentioned.

With respect to the temporal accuracy of the metronome-paced tone production, we saw a more pronounced negative asynchrony in the first 6 notes of the 11-note sequences when a hand repositioning or a large finger span was required. We regard those effects as manifestations of an increase in complexity, and they therefore are in line with our predictions. An increased negative asynchrony in the right hand might be explained in the following way. The participants might have strategically speeded up their performance before a complex situation in an attempt to neutralize beforehand the anticipated time loss associated with having to deal with that situation. That explanation is, in our view, particularly relevant in accounting for the effects of hand repositioning, as is explained later.

It should be noted that each complexity factor affected the growing negative asynchrony in tone production because the sequences progressed in somewhat different ways. Hand position affected only the first two notes. That finding demonstrates that the participants needed only a few notes to get used to the added complexity of the higher positions. In contrast, hand repositioning increased the negative asynchrony progressively more across the sequence. We think that finding reflected anticipation to locally increased task demands that had to be coped with between Notes F and G, where the repositioning had to be realized. The effect of the finger-span factor on the negative asynchrony of the right hand was distributed evenly across the whole sequence, possibly because that complexity factor was itself distributed equally across the analyzed sequence rather than confined to a single transition.

Regarding left-hand timing, the interaction between hand position and note number supported our rationale with respect to how expert guitar players react to and cope with increased complexity. Differential effects on Note D mainly caused the interaction. The finger was placed on the string considerably earlier on Note D than on the other notes. There are two aspects of the string change between Notes C and D that are relevant in that context. On the one hand, the movement required is more complex than that required on the other notes, because an open string (a string not stopped by a left-hand finger) is considerably higher above the fretboard than a stopped string. On the other hand, the first note after a string change can be prepared earlier than a note that does not occur after a string change, because, in the case of a string change, the string is not vibrating when the finger is placed on it, so the previous note is not damped. In our opinion, the observed increase in asynchrony was a clear example of an anticipatory reaction to the increased complexity of the string change. The conjoint increase in the variability of the asynchrony supported that view. However, the size of the asynchrony increase reflected the fact that the guitar players exploited the time available between the two notes to cope with the complexity because the required movements did not have consequences for the musical output and could therefore be performed well before the next tone needed to be realized. It is precisely because a string change affords the exploitation of the available time between successive notes that, even though that factor constitutes an increased task demand, at the outset of the present study we did not consider it to be a biomechanical complexity factor in guitar playing.

Concerning left-hand finger placement, the effect of the hand-position factor can most likely be explained by the variations in finger span associated with the changing size of the interfret spaces along the guitar neck. The size of the interfret space is larger in the low hand position than in the high hand position and therefore requires a larger finger span. Because there is more tolerance in the finger placement at the low end of the guitar neck, however, the fingers can be placed a little bit farther from the frets, thereby reducing the finger span. That argument was further supported by the effect of the finger-span factor. The effect of the hand-repositioning factor was similar to the effects of the other two factors, with the exception of the placement of the index finger on Note D. Our interpretation of that difference is that when no hand repositioning was required, the next position of the index finger stayed on the same fret, one string lower. Aspects associated with such a string change were discussed earlier. If hand repositioning is not needed, then it would be advantageous to keep the index finger away from the fret so that the risk of placing the finger on the fret would be minimized. If a hand repositioning is required, then the tolerance would not be needed, and the finger could be placed closer to the fret on the current string.

Functional Adaptations to Task Constraints

We have argued that professional guitarists react to an increase in complexity by increasing the negative asynchrony with the metronome, by exploiting the available preparation time for the left hand, and by reducing the finger span. The finding of a finger-span reduction supports the general idea proposed in the introductory comments that one of the ways in which guitarists contain the cost of fingerings is by keeping their joints in the middle of their range. The effects on left-hand timing and on the timing of tone production indicated another strategy of cost containment, namely, an optimal use of the available movement time by means of locally speeding up to compensate for an anticipated time loss caused by increased task demands in the upcoming movement sequence. In our view, the results of our study, taken collectively, support theories of motor behavior in which multiple task-constraint satisfaction is emphasized, such as that proposed by Rosenbaum and colleagues (Rosenbaum et al., 1995; Rosenbaum et al., 2001). Theories based on the optimization of a single parameter, for instance, output variance (Harris & Wolpert, 1998; Van Galen & Van Huygevoort, 2000), cannot account for the delicate increases of variability at one control level that create conditions that allow variability to be contained at another, task-goal related, control level (cf. Slifkin & Newell, 1998).

An objection that could be raised against our general conclusion is that the size of the effects we found was surprisingly small. Variability in all three dependent variables remained almost constant. On average, effects in the temporal domain were in the range of 5 ms in tone production, 25 ms in left-hand timing, and effects in the spatial domain were in the range of 4 mm. In our view, that finding not only reflects the very high proficiency of the participants but also demonstrates a great capacity for adaptation to increased task demands. Apparently, very small adaptations in timing or finger placement are sufficient to enable performers to adapt to local complexity changes. The objective of that strategy might be to keep the variability of right-hand timing constant, or at least within certain limits. That can be considered another convincing demonstration of motor equivalence—in the present case, in the domain of music performance (e.g., Lashley, 1942; Merton, 1972; Meulenbroek, Rosenbaum, Thomassen, Loukopoulos, & Vaughan, 1996; Raibert, 1977).

Remaining Issues

In addition to biomechanical factors that determine the complexity of left-hand finger movements, cognitive and musical factors play a role in the complexity of guitar playing, as was suggested by the results of the pretest. When, for instance, the same melody occurs several times at different pitch heights (a very common phenomenon in music), it might be biomechanically easiest to use different fingerings, each one optimally suited to one instance of the melody. Cognitively, however, it may be easier to choose a less optimal fingering that suits all, or almost all, instances of the melody. A possible explanation for that notion was offered by Baily (1985), who argued that the performer's internal representation of music might be in terms of movement, rather than sound. In motor control research, the "grammar of action" theory (Goodnow & Levine, 1973, p. 82; see Smyth, 1989; Thomassen, Meulenbroek, & Tibosch, 1991) offers another possible explanation. The process of selecting a fingering might be governed by cognitive rules concerning how to start and how to continue from a certain situation rather than only by biomechanical rules.

Finally, there are musical constraints on the fingering. The fingering has to facilitate the desired musical effect, such as phrasing or timbre. For instance, a long string generates more harmonics than a shorter string of the same diameter (i.e., the same string, but stopped at a higher fret); therefore, if a bright, clear sound is preferred, the string length should be maximized. If, on the other hand, a warmer sound is preferred, then the vibrating string length should be limited.

Cognitive and musical constraints are probably at least as important as, if not more so than, biomechanical constraints in guitar playing. However, that does not mean that biomechanical constraints are musically uninteresting. Insights into the biomechanical complexity of left-hand movements in guitar playing are, for example, highly relevant for didactical purposes. In addition, in music-technology contexts in which researchers try to develop computer algorithms that can automatically generate optimal finger-position sequences for any score of guitar music, insights into the complexity of left-hand finger movements might also have applied value (Heijink, 1999; Sayegh, 1989). Likewise, knowledge about the complexity of left-hand movements may contribute to improved physical models of guitar sound (Cuzzucoli & Lombardo, 1999).

In conclusion, in our view, the present study clearly showed that controlling and exploiting redundancy are important parts of classical guitar playing, and it is hardly surprising that players take many years of diligent study to attain a technical level that enables them to do so.

ACKNOWLEDGMENT

This research was conducted while the first author was an affiliate of the Music, Mind, Machine group at the Nijmegen Institute for Cognition and Information.

The authors thank Chris Bouwhuisen for his help in running the experiment and Dirk-Jan Povel for his helpful comments on an earlier version of this article. Furthermore, we thank two anonymous reviewers and Daniel Weeks for their helpful and constructive comments.

NOTES

1. We deemed that the influence of having to reach over the guitar body when playing in frets higher than the 12th fret was so great that we would have difficulty comparing the rightmost hand position with the other two hand positions; we therefore tried to avoid the guitar body. However, if the guitar body were to be avoided altogether, then the rightmost position could be no higher than the 5th fret; in that case, because the difference between the levels of the hand-position factor would be so small, we doubted we would find any effect at all. We chose the rightmost position such that only in the conditions that required a hand-position change did the part of the stimulus after the sixth note require the participant to reach over the guitar body.

2. Locations B and E were not always played with the same fingers (see Figure 1a). In the large finger-span conditions, those locations could not be played with the ring finger, because the finger span would be so large in the left hand position that the participants would not be able to play it. A post hoc Student's *t* test showed, however, that the positions for those two fingers were not significantly different from each other.

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Submitted February 6, 2001
Revised September 10, 2001