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DO PERCEPTION AND MOTOR PRODUCTION SHARE COMMON TIMING MECHANISMS: A CORRELATIONAL ANALYSIS *

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The two experiments of this study exploited individual variation in timing ability to ask whether the production of time intervals by different motor effectors and the judgement of perceptually based time intervals all share common timing mechanisms. In one task subjects produced a series of taps, attempting to maintain constant intervals between them. Individual differences in variability of the produced intervals correlated across the effectors of finger and foot. That is, people that were 'good timers' with one effector tended to be 'good timers' with another. Besides timing motor production, the subjects also judged durations of brief perceptual events. The acuity of perceptual judgements correlate substantially with regularity of motor production. Further results involving maximum speed of motor production suggested that variability of motor timing comes from two sources, one source in common with perception, and hence called clock variability, and the other source in common with motor speed, and hence called motor implementation variability. The second experiment showed that people high in skill on the piano were better at both types of timing on the average than control subjects with no expertise.

Many motor activities must be precisely timed for their proper execution. This is obvious in skills with muscial instruments in which mistiming of motor action can diminish the quality of the music, but precise timing also is characteristic of other skills where the execution of one component too early or too late could make the skill less effective. The goal for our research is to understand more about the timing mechanisms involved in such skills.

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One fundamental question concerns whether different effectors – fingers, arms, feet, etc. – share mechanisms of timing or whether each system is timed independently of the others. One approach to this question involves time sharing. If two motor activities share common timing mechanisms, then it might be the case that their concurrent production would be difficult if they are timed differently. Yamanishi et al. (1980) found that when the forefinger of each hand is tapped at a pace of once per second, simultaneous tapping of the two fingers produced mutual interference unless the fingers were timed either in phase or 180 degrees out of phase. Similarly, Klapp (1979) found that two hands tapping slightly different temporal patterns produced interference whenever the overall cycle times of the two patterns were not equivalent. Moveover, Klapp (1981) found similar rules to apply to the coordination of voice and hand, two effectors very different from each other. Such interference when two different effectors follow different temporal courses suggests a timekeeper in common to the effectors.

A second approach to the question of common timing, and one pursued in the two experiments in this paper, involves the exploitation of individual differences. When subjects produce a series of regularly spaced taps, the intervals between taps actually vary (see Michon (1967) for a seminal investigation of intertap variance). Subjects differ in how much their intertap intervals vary. This raises the question of whether variance correlates across different effectors. If different effectors have their own timing systems, it might be the case that precision of timing with one effector would bear no correspondence to precision with another. On the other hand, if some common timing mechanism was used by different effectors, then it would be expected that subjects who are relatively precise with one effector should also tend to be relatively precise with another. Although such a correlation might be due to reasons other than a common timing mechanism, correlation of variances constitutes a useful initial approach to the question. Moreover, correlations of variances with other variables might clarify the reasons for whatever relations exist.

Besides timing movements, people can judge the duration of perceptual events, and often such durations are on a scale similar to that of relatively fast-paced motor activity. The question arises whether the mechanism used for perceptual timing has any commonality with that used for motor production timing. Intuitively it seems that such must be the case. If one hears a pair of clicks separated by an interval of a few hundred msec, the interval can be reproduced by a pair of taps. A perceptually based time interval is translated into motor production of an equivalent interval. Perhaps based on such reasoning, investigators such as Michon (1967) suggest that the same timing mechanism underlies both tasks: 'The explanations offered to account for the temporal aspects of behavior ... are essentially identical for (anticipatory) timing in key tapping or rhythmic performance. Consequently we will accept key tapping as a valid tool to study the mechanisms by which human beings evaluate short intervals of time' (1967: 2). However, some (e.g., Treisman 1963: 16) have suggested that timing of closely spaced rhythmic movements is based on different mechanisms than perceptual timing. Thus, investigation is needed into the issue of whether a common timing mechanism underlies perception and production.

One approach to the issue utilizes time sharing. Recently Pokorny (1985) has found that the presence of tones within the intertap intervals affects the tap timing. The amount of interaction depends on the exact temporal relationship of tone and interval. Such a result suggests that aspects of timing are in common to perception and movement. The current study approaches the issue by again using a correlational approach. Is it the case that people who are relatively good at motor timing are also good at perceptual timing? Besides inquiring about the commonality of timing between different effectors, the two experiments reported here also investigate the relation between the accuracy of motor timing and the accuracy of perceptual timing. An earlier study by Smith (1957) did find correlations of about 0.45 between the discrimination of intervals and the accuracy of producing intervals. The present studies seek to replicate that work, extend the analysis to different effectors, and analyze correlations with other tasks to delve further into the issue of common timing.

In the first experiment each subject performed a number of tasks, including the production of regular intervals by tapping either their finger or foot and comparing the durations of time intervals between clicks. One question concerns whether variability of timing with the finger is correlated with that of the foot. That is, is regularity of timing a property only of the effector or is it a more central property? A second question inquires whether motor timing variability correlates with perceptual timing accuracy.

The second experiment takes a slightly different approach based on group differences. High level skill in piano playing should require both relatively precise motor timing and precise perceptual timing. Thus, one would expect highly skilled piano players to be better at timing on the average than control subjects with no expertise. Such could be the case either because good timing ability is a prerequisite for attaining high level skill on piano, or conversely, because extensive practice on the piano might lead to the acquisition of good timing. In either case, it would be useful to know whether simple measurements of perceptual and motor timing relate to high level skill. If pianists are better than non-pianists on both perceptual and motor timing, this would provide additional evidence for their covariation.

Experiment 1

The primary questions in this experiment concern whether regularity of motor timing correlates across two different effectors, finger and foot, and whether the regularity averaged over those two effectors correlates with the accuracy of perceptual timing. To study motor regularity, an *S* first listened to a click that occurred every 400 msec [1] and attempted to synchronize tapping on a key with the clicks. After several synchronizing taps, the clicks stopped but the *S* continued to tap at the target rate. The measure of motor timing regularity is the standard deviation of the intertap intervals from that latter period. To determine whether motor timing regularity was correlated across effectors, the standard deviation of the foot, averaged across many bouts of tapping, was correlated across *S*s with the standard deviation of the finger.

Perceptual timing accuracy was based on a task in which *S*s compared two successive intervals. An *S* first heard a pair of clicks separated in their onsets by 400 msec. This standard is the same as the target interval in the motor production task. A second after the standard, the *S* heard another pair of clicks of slightly greater or less separation and judged whether the second interval was longer or shorter than the first. A series of such judgements yielded upper and lower thresholds that indicated how long or short a comparison interval must be to normally be perceived as longer of shorter than the initial standard interval. The difference between the upper and lower thresholds constitutes a measure of perceptual timing acuity. Correlating the perceptual scores with the standard deviations of the finger and foot intertap intervals indicates the degree to which perceptual timing is related to motor timing.

[1] Inquiry into the nature of timing has a long history in psychology (see an excellent review by Allan (1979)). Much earlier work deals with the subjective passage of time (e.g., Michon 1977), often over intervals of several seconds or more. In the current study, the focus of attention is on an understanding of timing in motor skills rather than on the subjective experience of time. This leads one to investigate the control and perception of time of much briefer intervals, less than a second, as may characterize timing in fast-paced motor skills such as music production. While it may be the case that the timing mechanisms of relatively fast motor timing and relatively long subjective time are related, there is no a priori reason for thinking that they are similar. Since the focus here is on motor skill, the study concentrates on a relatively short time interval of 400 msec.

In addition to investigating perceptual and motor timing, the present experiment also was concerned with the maximum speed of motor activity. In a previous study by Keele and Hawkins (1982), it was found that the maximum speed at which an effector could be moved back and forth in tapping was quite highly correlated across effectors: People fast in reciprocal action with the finger also tended to be fast with the thumb, wrist, forearm, and foot. Each effector also moved at roughly the same speed with mean intertap intervals between about 150 and 230 msec. These results suggested that some central factor controlled speed. Keele and Hawkins also found that the speed at which people normally produced handwriting was correlated with speed of all the effectors, including the foot. Since handwriting involves reciprocal motion of the wrist and of thumb and fingers, plausibly maximum speed of reciprocal motion in general constrains the speed of handwriting.

A reason for including the study of speed in the present experiment was to investigate the possible relation of timing variability to speed. Freund (1983) has argued that the speed of reciprocal movement approaches a limit set by the minimum contraction time of the muscles involved. If there is any variability in the timing of the successive neural inputs to the muscle antagonists that produce reciprocal movement, the movements would be slower than the limits set by muscle contraction speed. The more variable the timing, the slower should be reciprocation speed. In this study a measure of timing variability is extracted from submaximal speed, namely from the motor timing task. By correlating motor timing variability with the mean intertap interval at maximum speed, it can be determined whether increased motor variability contributes to slower motor speed. As *S*s approach maximum speed, often the intertap intervals markedly increase in variance, in part due to momentary pauses in movement. The root cause of such 'blocking' of movement may be due to mistiming of neural signals. The degree of mistiming may be best judged at a submaximal rate, such as at the 400 msec pace in the timing tasks of the present study.

Finally, *S*s copied a sentence several times at their normal writing speeds. One intent was to correlate handwriting speed with maximum speed of reciprocal movement in an attempt to replicate the earlier result of Keele and Hawkins (1982) that found a tendency for people with slower maximum tapping rates to be slower writers. Presumably, such a relation is due to a tendency for people to adopt spontaneous rates that approaches but does not reach their maximum speeds. The second intent was to investigate the relation between handwriting quality and timing variability. In one conception of handwriting (Vredenbrecht and Koster 1971), letter shapes are produced by the proper timing of movement on two orthogonal axes of movement. From such a perspective, it might be expected that variation in shape of the same letter from trial to trial, which is one measure of handwriting quality, would be correlated with timing variability in the timed tapping task.

Method

Subjects

Sixteen men and sixteen women were selected as *S*s from the pool of *S*s available to the Cognitive Laboratory at the University of Oregon. The *S*s were all between 18 and 35 years of age. All were right handed and were native speakers of English. *S*s were selected who claimed to use cursive handwriting as their normal mode of writing. Each person participated in two sessions and was paid $3.50 per hour.

Tasks

*S*s performed both timed and speeded tapping tasks with both their right forefinger and right foot. The tapping apparatus for the finger was a key of 1 cm square that rested atop a microswitch. Movement of about 1.5 mm actuated the switch. The force required was about 0.8 newtons. The microswitch was mounted on the top side in the center of a block 8 com by 5.5 cm and with a depth of 2 cm. An *S* grasped the block between his or her thumb and small and ring fingers with the middle finger resting on the top surface. The key was then tapped by slight movement of the slightly curled index finger. The purpose of controlling the movement in this fashion was to restrain movement to the index finger without involvement of the wrist.

The tapping apparatus was a microswitch mounted on a platform. For foot tapping, *S*s kept their heels planted and moved the ball of the foot up and down about 1 to 2 cm, striking the switch with the ball of their feet. For heel tapping the ball of the foot remained planted and the heel was raised and lowered. All *S*s wore flat-bottomed jogging shoes. The microswitch moved about 1 mm for closure and required a force of about 2.5 newtons. All tapping was conducted with *S*s in a seated position.

For each tapping bout of the timing task, the initial press of the appropriate finger or foot key actuated a train of clicks with onsets separated by 400 msec. *S*s attempted to synchronize their finger or foot movements with the click for a series of 20 synchronization taps. After the click stopped, the *S* continued tapping at the same rate for 30 more taps. Following each such bout, *S*s received feedback on a video display regarding their mean intertap interval and the standard deviation of intervals. Each *S* had 24 such tapping bouts with the finger and 24 with the foot spread over 2 experimental sessions. The data to be reported were taken from the continuation phase after the click stopped.

The speed tapping task involved the same apparatus. When a ready signal appeared on a video screen, an *S* initiated a trial with a first tap and then tapped as rapidly as possible for a bout of 4 sec. The mean intertap interval was calculated for each bout. Over the two experimental sessions, there were 6 bouts for each of finger, forefoot, and heel movements. Two foot movements were investigated on the speed task because some pilot work had suggested that they might yield different outcomes. As it turned out, differences between forefoot and heel movements were minimal.

For the perceptual timing task, *S*s compared successive intervals generated by two pairs of clicks. The onset-to-onset interval between the first pair of clicks was always 400 msec. One sec after the offset of the first pair of clicks a second pair was presented. Half the time the second interval was 'shorter' and half the time it was 'longer'. An adaptive procedure called PEST (parameter estimation by sequential testing) and described by Pentland (1980) was used. Depending on whether an *S* judged a comparison interval to be shorter or longer than the preceding standard, on a succeeding trial the comparison interval was lengthened or shortened. Using this staircase method, both an upper and a lower threshold were estimated. A threshold is defined as one standard deviation from the point of subjective equality assuming a logit distribution. Approximately speaking, the lower threshold is that interval at which approximately 75% of the time the *S* will say it is shorter than the standard 400 msec interval. The upper threshold is that interval at which approximately 75% of the time the *S* will say it is longer than the standard 400 msec interval. The difference between the upper and lower threshold is a measure of perceptual timing accuracy. Such a measure was taken on each experimental session and each measure was based on 35 judgements for the high threshold and 35 for the low threshold.

For the handwriting task the *S*s repeatedly wrote the sentence, 'apples and pears are good'. The sentence was designed to have no dotted 'i's or crossed 't's, which would require return movements, and it had a mixture of ascending and descending letter parts that would facilitate the assessment of regularity. The *S*s had 2 practice reproductions of the sentence and then they produced the sentence 5 times at their normal speed while the total time of writing was recorded. The handwriting task was administered on each day. Later three judges rated each written message on a five-point scale on how variable the letter shapes were. An attempt was made to ignore the quality of writing style and concentrate on the degree to which the same letter varied in shape on different occasions.

Design

In a study of individual differences it is important that each *S* be run through conditions in the same order to ensure that differences among *S*s are not due to differences in the order in which they encounter the conditions. Thus, the only counterbalancing involved the order of conditions from one day to the next.

Results and discussion

The analysis of results is broken into sections that include only correlations among variables selected to make major points. A more complete correlation matrix among the many variables in this experiment is presented in table A.1 in the appendix.

Motor timing

Motor timing accuracy is assessed by the standard deviation of the intertap intervals produced after cessation of the pacing tone during which timing is internally generated. *S*s sometimes show slight drifts in the mean intertap interval from beginning to end of a tapping bout, and such a drift adds slightly to the overall variance of intervals. To avoid such contamination, a linear trend line was fitted to the intervals and the standard deviation of the departures of the intertap intervals from that predicted by the trend line were calculated. Averaged over all 32 *S*s and both sessions, the mean standard deviation for the finger is 20 msec and for the foot it is 21 msec. Thus, finger and foot are equally accurate with the standard deviation of each about 5 percent of the mean interval being produced.

The issue of primary interest is the correlation across *S*s between finger and foot variance: Is it the case that people with high finger variance tend also to have high foot variance? The correlation of the two variances is 0.44 in this study ($p < 0.01$). The reliability of the finger and foot scores (based on day 1–day 2 correlations) is 0.87 for the finger and 0.86 for the foot. When these are used to correct for attenuation, the correlation between finger and foot is estimated to be 0.51. In two pilot studies, one with 19 *S*s and one with 30 *S*s, that examined finger and foot timing, comparable uncorrected correlations of 0.46 and 0.55 were obtained between foot and finger variability. In another study comparing finger and forearm variability (Keele et al. n.d.) a correlation of 0.90 was obtained. Thus, it appears that there is considerable commonality of timing ability across effectors.

One might expect that if different effectors share a common timing mechanisms, the correlation of timing variances would be even higher than found here. However, more than one factor probably contributes to timing variation. One source of variation might be in a timing mechanism itself, but additional variation might be present in the system that implements movement. Perhaps the implementation variance is uncorrelated across effectors. As a result, the correlation of total variances might be reduced. Wing (1980) and Wing and Kristofferson (1973) have proposed a model for separating variance due to a common timekeeper (a clock) and that due to the motor system.

By the Wing and Kristofferson theory, total variance σ_T^2 is equal to the sum of clock variance σ_C^2 and motor variance σ_M^2. That is, assuming clock and motor variance are independent: $\sigma_T^2 = \sigma_C^2 + 2\sigma_M^2$. Total variance is of course calculated from the variance of the intertap intervals. Wing and Kristofferson proposed a method of calculating motor variance. Once motor variance is calculated, clock variance can be estimated by subtracting motor variance from the total variance. Briefly, the calculation of motor variance is based on the idea that variation in the duration of motor implementation produces a negative correlation between adjacent tapped intervals: long intervals tend to be followed by short and vice versa. To appreciate this, suppose that by random chance a particular movement implementation time is short. The result will be to make the preceding interval shorter than it would have been had implementation time been randomly long. The next clock interval is assumed to be unaffected by variation in the preceding implementation time, since the clock and implementation processes are independent. Therefore, a short duration motor implementation will not only shorten the preceding interval but lengthen the next. Likewise, a randomly long implementation time will lengthen the preceding interval and shorten the following one. Thus, a result of variation in implementation duration is not only to contribute to overall intertap variation but also to introduce a negative covariation between adjacent intervals. The magnitude of the covariation of successive intervals serves as an estimator of the motor implementation variance (cf., Wing (1980) for details).

Applying the Wing and Kristofferson model to the present data, if a common clock is used for finger and foot, the estimate of clock variance, averaged over *S*s, should be about the same for the two. This is the case. Clock standard deviation is estimated at 14.4 msec for the finger and 15.7 msec for the foot. The motor implementation variances also turn out to be similar – on average 9.3 msec for the finger and 9.7 msec for the foot. The more crucial prediction for this study is that clock variances should be more highly correlated between finger and foot than are total variances. This prediction failed to materialize. The correlation of clock variances between finger and foot was only 0.08. In addition, the correlation between motor variances was also essentially zero at 0.04. In the two pilot studies that also examined this issue, the clock and motor correlations were inconsistent.

The failure to find high clock correlations may stem from certain violations of assumptions of the Wing and Kristofferson model. The model assumes that both successive clock intervals and successive motor implementation times are independent random variables. The fact that intervals separated by more that one intervening interval (not just adjacent intervals) also are correlated with each other for some *S*s in some conditions is an indication that those assumptions are violated. We did attempt to fit a more complex model developed by Wing (1977) that takes into account violations of the basic assumptions, but there was no marked change in outcome – clock variances still did not correlate highly across foot and finger. A problem, however, is that the complex model requires much more extensive data gathering for each *S* than was practical for the many *S*s of this study. Thus, application of the Wing and Kristofferson model to the present data cannot be clearly evaluated.

To summarize up to this point, the present study finds a sizeable correlation between finger and foot timing variance, suggesting a common timing mechanism. However, an attempt to isolate that portion of timing variance due to a central timer by using a model of Wing and Kristofferson was not fruitful. Later, when considering the maximum speed of reciprocal action, other evidence will be presented for separable contributions to timing variance of a central and peripheral sort.

The relation of motor timing to perceptual timing

In the perceptual timing task, *S*s judged whether the second of two intervals was shorter or longer than the standard first interval of 400 msec. For each *S* an upper and a lower threshold was determined. Subtracting the two thresholds yielded a score of perceptual timing accuracy of 36 msec averaged over all 32 *S*s and over both days. This value is equivalent to two standard deviations. Thus, half the value, one standard deviation, is 18 msec, which is roughly comparable to the 20 and 21 msec standard deviations of motor variance in the production task. The reliability of the perceptual accuracy measure was 0.82.

The primary question concerning perceptual timing accuracy is its correlation with motor timing variability. As a reminder, motor variability is based on the standard deviation of intertap intervals following offset of pacing clicks at intervals of 400 msec. To obtain a more stable measure of motor timing variability, the standard deviation for foot and finger of each *S* was averaged, and this average score was correlated with perceptual timing accuracy across *S*s. The correlation is 0.53 ($p < 0.01$). This correlation increases to 0.60 when corrected for attenuation due to the level of reliability of the perceptual and motor scores.

Thus, people that exhibit relatively low variability in motor timing also tend to have relatively good acuity in the judgement of duration of perceptual events. In turn these results suggest common timing mechanisms between perception and production.

Relation of motor speed to motor and perceptual timing

Each *S* also engaged in reciprocal tapping as fast as possible with finger, forefoot, and heel. Across *S*s the mean intertap intervals at maximum speed were 182, 185, and 176 msec for finger, foot, and heel, respectively. The mean intertap intervals correlated across *S*s 0.52 between finger and forefoot, 0.64 for finger and heel, and 0.58 for foot and heel. These results are similar to those of Keele and Hawkins (1982). Some common mechanism appears to limit speed to about the same value across differing effectors and produce a correlation across *S*s.

Table 1
Correlations between motor timing, motor speed, and perceptual timing.

	Motor timing	Perceptual timing
Motor speed	0.46	0.18
Motor timing		0.53

Freund (1983) has pointed out that reciprocal movement can occur no faster than muscles can contract, and he has claimed that reciprocation rates approach that limit set by the muscles. Perhaps the muscles that are involved in moving the finger, heel, and foot have similar contraction times, and if so that would explain why the reciprocation rates are similar. However, one reason why individuals may differ from one another on speed may derive from individual differences in timing. Maximum speed cannot be achieved unless the signals actuating opposing muscles for reciprocal movement are optimally timed on each movement. Any variation in timing should result in movement rates less than that theoretically possible. It might be expected, therefore, that people with greater timing variability, where timing is assessed at submaximal speeds, would have slower rates of reciprocal movement. To check this possibility, a mean speed was calculated for each S by averaging the mean intertap intervals for finger, foot, and heel. Likewise for motor timing, variability based on tapping at a target interval of 400 msec was averaged over foot and finger. These mean scores correlated 0.46 ($p < 0.01$). However, motor speed correlated only 0.18, a non-significant amount, with perceptual timing accuracy.

Thus, variability of motor timing correlates with speed but perceptual accuracy does not. Recall also that perceptual and motor timing correlated 0.53. These three correlations are shown in table 1 to highlight their relationships. The pattern of correlations suggest that variability of motor timing is indeed one reason for speed differing across individuals. However, since perceptual timing does not correlate with speed, it appears that motor timing variability is composed of two separable components. One component is in common to perception and production, and we will call that the central component or the clock component. In addition, motor timing adds another source of timing variance particular to the motor system and that portion correlates with motor speed. We will call that latter component the motor component. The multiple correlation of motor timing with motor speed and perceptual timing is 0.68.

Why does only motor timing variability and not perceptual timing correlate with speed? It is possible that when movements are made at maximum speed there is no central timing of the impulses to the muscles. Rather after some refractory period a signal sent to one muscle is followed immediately by a signal sent to the opposing muscle, producing a movement reversal. All variation in timing at maximum speed therefore may be due to variation in implementation time of movement. This idea is similar to that expressed in the Wing and Kristofferson model (1973; Wing 1980). Motor timing variation consists of two components, clock variation and variance in duration of motor implementation, and only the latter may correlate with speed.

Table 2
Correlations between speed and timing variance of different effectors.

	Motor timing variance	
	Finger	Foot
Effector speed		
Finger	0.28	0.39
Foot	0.22	0.30
Heel	0.42	0.37

Clock variance is common to both motor and perceptual timing. The question may be raised whether variation in motor implementation is specific to each effector or whether it is common to differing effectors. If the variation is effector specific, then maximum speed of an effector should be more closely related to timing variance of that same effector than to timing variance of other effectors. On the other hand, if implementation variance is general to different effectors, then speed of one effector would correlate just as highly with timing of a different effector as with timing of the same effector. Data in table 2 support the latter conception: Motor implementation variance appears to be in common to different effectors since there is no tendency for correlations of speed and timing to be higher within the same effector than across effectors. It might be noted that these correlations are rather low. The higher correlation of 0.46 between speed and timing when averaged over effectors is likely due to averaging out effector-specific variation.

Handwriting

Each *S* produced a sample of handwriting from which speed of writing was measured and variability of letter shapes was judged. It was predicted that speed of writing would be related to speed of tapping under instructions to tap as rapidly as possible and that writing variance would be related to timing variance. Neither of these predictions were confirmed as there were no significant correlations between speed of writing and speed of any of the effectors nor were there significant correlations between variability of handwriting and variance of timing with either finger or foot. This study fails to replicate, therefore, the finding of Keele and Hawkins (1982) that tapping speed and writing speed are related. In other unpublished work we also failed to replicate that result.

Experiment 2

The question of interest in this study is whether timing and speed measures reflect basic processes that underlie skill. We attempted to test this issue in the first experiment by correlating tapping based measures of speed and timing with variability of letter shape and speed in handwriting. No correlations of note were found. In this second experiment the possibility that basic timing and speed abilities are important for skill is tested by analyzing highly skilled piano players. Presumably to become an accomplished pianist requires years of practice, but despite practice, perhaps one cannot reach such a high level unless basic timing is acute and the person is capable of high motor speed. Conversely, it is possible that the years of training in piano would lead to the acquisition of good timing and high speed of reciprocal movement. Some investigators, such as Shaffer (1981), have assumed that a central clock underlies the control of movement in piano playing. Thus, such a skill is an appropriate one for determining the relevance of basic timing and speed abilities to motor skills.

To test the issue a group of highly skilled pianists were run on the same tasks as the *S*s in experiment 1. The comparison of pianists with controls constitutes another test of whether perceptual and motor timing covary, but using group differences rather than individual differences.

Method

Subjects

Sixteen highly skilled pianists were selected. All either taught piano at the University of Oregon School of Music, were graduate students at the university who specialized in piano, or were pianists from the community who were recommended by the piano faculty. Half the pianists were male and the other half were female. The control *S*s were the 32 *S*s of experiment 1 none of whom were highly skilled pianists.

Tasks

The tasks were exactly the same as in the first experiment: (1) Timed motor tapping with a target intertap interval of 400 msec, (2) comparison of the durations of two successive intervals generated by pairs of clicks, one of which was 400 msec, and (3) tapping the finger, forefoot, and heel as rapidly as possible. The *S*s of this experiment received the same number of trials on each task and in the same order as in experiment 1.

Table 3
Speed and timing for pianists and non-pianists.

	Pianists	Non-pianists
Speed: Mean ITI (msec)		
Finger	160	182
Foot	181	182
Heel	182	176
Motor timing: *SD* (msec)		
Finger	15.3	20.1
Foot	17.7	21.3
Perception range (msec)	25	36

Table 4
Total, clock, and motor variabilities for pianists and non-pianists by the Wing and Kristofferson model. Standard deviations in msec.

	Pianists		Non-pianists	
	Finger	Foot	Finger	Foot
Total variance	15.3	17.7	20.1	21.3
Clock variance	12.1	13.4	14.4	15.7
Motor variance	5.8	7.9	9.3	9.7

Results and discussion

Table 3 compares the results of motor timing, perceptual timing, and speed of the pianists with the non-pianists. The pianists were less variable on motor timing, had a smaller difference between upper and lower thresholds on the perceptual timing task, and were faster with the finger (all $p < 0.01$). Little difference occurred between pianists and non-pianists on foot and heel speed.

This experiment suggests that abilities of motor and perceptual timing and at least finger speed are relevant to one skill, piano playing. In addition, the group differences in timing confirm those of the individual differences in experiment 1 that motor and perceptual timing covary, since pianists are better than non-pianists on both. These latter conclusions can be further examined by looking at individual differences among the pianists. For the 16 pianists, motor timing variability of the foot correlated 0.61 with variability of the finger ($p < 0.01$). This result is similar to that of the control *S*s (experiment 1) and again suggests a common timing mechanism across effectors. For the pianists, motor timing variability averaged across finger and foot correlated only 0.35 with perceptual accuracy, a value that is not significant with only 16 *S*s. Nonetheless, the correlation is in the correct direction and is well within the range of error for 16 *S*s were the true correlation about 0.5.

One final comparison between pianists and non-pianists concerned the breakdown of total motor variance into clock and motor implementation components based on the Wing and Kristofferson model (1973; Wing 1980). Table 4 shows the results. Pianists have both a smaller motor delay variance ($p < 0.001$) and a smaller clock variance ($p < 0.001$) than non-pianists.

General discussion

In recent years cognitive psychology has been remarkably successful in the analysis of various coding systems that underlie performance. For example, both experimental methods with normal subjects and the analysis of patients with neurological deficits have led to the isolation of phonetic, visual, and semantic codes used in the process of reading.

In addition to the codes themselves, it might be supposed that general purpose mechanisms exist for operating upon those codes. An example of such a mechanism involves shifting attention, which may involve general operations performed on several codes (see Posner (1985) for a discussion of this view). Another possible general purpose mechanism is that of a timing mechanism or a clock. Is it the case that a general purpose timer is drawn upon by differing effectors and also for perceptual judgements of duration? In a broad program we are investigating this issue using each of the three methods – individual differences, time-sharing, and neurological deficit.

The present study uses the first of those methods, that of individual differences. If the same clock, or at least parts of the clock, underlies both motor and perceptual timing, then one ought to find correlations in the efficiency with which differing individuals perform with various effectors and also correlations between motor timing and perceptual timing. The present experiments confirmed both of these expectations: The first experiment showed motor timing accuracy to correlate between foot and finger. Motor accuracy averaged over both of those effectors correlated about 0.6, when corrected for attenuation, with accuracy of perceptually based time judgements. The second experiment showed a similar covariance of perceptual and production timing across people of high and low skill on the piano. At the same time the group differences indicate that the basic timing and speed tasks used are relevant to performance on some important human skills.

A second approach to the study of timing makes use of a time-sharing methodology. One of us (Pokorny 1985) has examined the interaction of motor timing with co-occurring perceptual events. For the motor task, subjects heard a short set of clicks spaced at 800 msec, and then they attempted to reproduce the timing with a series of evenly spaced taps. During some tapping bouts, tones of varying duration, loudness, or pitch occurred in some of the intertap intervals. The presence of the auditory events affected the timing of the intervals in which they were embedded. Interestingly, the effects of the tones are similar regardless of whether the subjects made decisions about tonal duration or about pitch or loudness and even whether the tones were attended. The magnitude of the tones' effect on the intertap interval varied with the temporal placement of the tone within the interval. These interactions suggest that there are common timing mechanisms between perception and movement, but the interactions are passive and do not depend on attending to the temporal properties of the perceptual events.

We have also begun to examine the concept of a clock by analyzing patients with timing disorders. In a case study of a Parkinson patient with timing problems (Wing et al. 1984), the patient exhibited a clock disorder based on the Wing and Kristofferson (1973) model of timing. In preliminary results we have found suggestive evidence that a clock disorder also occurs as a result of cerebellar damage (Keele et al. 1985). If correct, the results suggest that the clock system involves an interaction among two or more disparate brain systems. Another patient with peripheral nerve damage also showns inflated motor timing variance on one hand compared to the other, but in this case the increased variance appears due to increased variance of implementation time rather than clock variance (Ivry and Keele 1985). These preliminary studies suggest that clock and motor implementation contributors to the variance of motor timing emanate from different neural structures. Unfortunately, these patients did not lend themselves to a test of whether or not they had a perceptual timing deficit. Our hope is that the study of patients will provide converging evidence to that of individual differences in timing and time-sharing of tasks for the concept of a central clock shared by motor and perceptual systems.

Although the individual differences investigated in this study are consistent with the concept of common timing mechanisms for perception and movement, certain limitations of the study preclude firm conclusions. An alternate hypothesis is that the correlations among the tasks reflect some sort of general noise factor. Such an interpretation is not clearly ruled out, but two observations are relevant. The first observation concerns the relation of timing to maximum effector speed. The motor timing task was related to speed while the perceptual timing task was not. Since motor timing is correlated with perceptual timing, it appears that motor timing variance derives from two sources, one in common with perception and the other in common with speed, making the concept of a single noise factor that explains motor timing less tenable. A second observation of relevance is from a study of force control by Keele et al. (n.d.). In that study subjects were tested for variation in force from one movement to another when they were attempting to reproduce the same force. Although force control of the finger, foot and forearm correlate highly with each other, none of them correlate systematically with either motor or perceptual timing accuracy. These observations suggest that the correlation between motor and perceptual timing is due to more than a general factor of noise.

A more sophisticated approach to the analysis of motor timing might attempt to separately measure clock and motor implementation components of motor timing. If this was possible, then one should find higher correlations of the isolated clock component of motor timing with perception than total timing variability with perception. As mentioned earlier we used the Wing and Kristofferson (1973; Wing 1980) model to decompose foot and finger timing into clock and motor components. However, this decomposition failed to yield the expected high correlations between clock of the finger and clock of the foot. Moreover, it failed to yield larger correlations between the clock component and perceptual timing accuracy than between overall motor variability and perceptual accuracy. One problem with the approach is that clock variance in the Wing and Kristofferson model is calculated indirectly by subtracting the estimate of motor variance from the total variance of intertap intervals. Any error in calculating motor variance (perhaps because of violating assumptions), also would alter the clock estimate.

In another study (unpublished) we devised another method for isolating clock variance. The idea was based on work by Wing (1980), who showed that clock variance (estimated with the Wing and Kristofferson model) increased linearly with the mean intertap interval being produced. Motor implementation variance was unaffected by intertap interval. Such a finding makes sense in that the larger the interval being timed by the clock the more variable it should be. This implies that the growth in total variability of intertap intervals as the target interval increases in length is due only to the presumed clock. A further implication is that clock acuity can be measured by the slope of the function relating total variability to mean intertap interval. Such a method of measuring clock acuity does not depend on the intermediate step of calculating motor implementation variability.

To pursue this idea we had people tap at four different target intervals ranging between 350 and 650 msec with both finger and forearm. People also compared the length of click-defined time intervals with the same four standard intervals used in the motor task. For each subject and each task, a slope was calculated that related accuracy of motor timing or perceptual timing to the magnitude of the target interval. Our expectation was that the slopes would be correlated: Subjects having high slopes with one effector would also show high slopes with the other effector and with the perceptual task as well. The results exhibited no significant correlation between the slopes. However, the accuracy scores averaged across intervals did correlate between effectors and effectors with perception, replicating experiment 1, but the attempt to uncover larger correlations by isolating a pure clock measure from slopes was a failure.

We are uncertain of the reasons for these discrepancies. The correlations among motor timing, perceptual timing, and speed suggest a decomposition of motor-based timing into clock and motor implementation components, but these components appear not to map into the clock and motor implementation components of the Wing and Kristofferson model.

Appendix

Table A.1 exhibits a more complete matrix of the correlations from experiment 1 than is described in the body of the text. The speed task refers to the situation in which subjects tapped with finger, foot, or heel as rapidly as possible, and the values calculated are the mean intertap intervals. The timing task refers to tapping at a target interval of 400 msec with finger or foot. The timing scores are the square roots of total variance of the intertap interval, clock variance, and motor implementation variance. Clock and motor variance are calculated in accordance with the Wing and Kristofferson model (1973; Wing 1980). The perception range refers to the accuracy score from the task of comparing intervals defined by clicks. Writing speed refers to the time to produce five samples of handwriting, and writing variance refers to ratings of the variability of letter shape. All the predicted correlations should be positive: larger mean intertap intervals on the speed task should be positively correlated with variances on the timing tasks and with handwriting time; timing variances should be positively correlated with each other and with handwriting variability. The number of subjects in the study was 32. Correlations at or above 0.30 would be significantly greater than 0 using a 1-tailed test at the 0.05 level if each correlation was considered singly.

Table A.1

	Sp fing	Sp foot	Sp heel	Tim fing	Cl fing	Mot fing	Tim foot	Cl foot	Mot foot	Per	Wr sp
Speed foot	0.52										
Speed heel	0.64	0.58									
Timing finger	0.28	0.22	0.42								
Clock finger	0.13	0.16	−0.03	0.46							
Motor finger	0.19	0.13	0.48	0.81	−0.12						
Timing foot	0.39	0.30	0.37	0.44	0.29	0.32					
Clock foot	0.32	0.14	0.35	0.35	0.07	0.34	0.82				
Motor foot	0.27	0.35	0.16	0.24	0.39	0.04	0.63	0.09			
Perception	0.31	0.01	0.20	0.45	0.35	0.29	0.45	0.30	0.35		
Writing time	−0.05	0.26	−0.03	0.04	−0.11	0.10	0.02	0.08	−0.08	−0.03	
Writing var.	−0.17	−0.23	−0.24	−0.37	−0.02	−0.35	−0.16	−0.26	0.02	−0.17	−0.34

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