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# SEARCHING THROUGH TIME:

# SHAPING ELIMINATES THE SIMPLE INTERVAL-RATIO ADVANTAGE

# FOR UNIMANUAL TAPPING

A Dissertation in

Psychology

by

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## ABSTRACT

The current study advances the argument that representational factors (i.e., cognition and perception) play an important role in the control of rhythmic movements. The research strategy that was used was based on the idea that it is plausible that different methods for inducing motor output engage various information processes to different degrees. The information processes thought to be engaged by a particular method for inducing motor output were then related to performance.

Evidence is presented that is consistent with the hypothesis that the source of the 1:2 and 2:1 interval-ratio advantages in unimanual tapping is internal representations based on real-time sensory events associated with target performance. This is accomplished by demonstrating that the 1:2 and 2:1 advantages were observed in tasks that did not provide participants with knowledge of results or KR (i.e., imitation tasks and continuation task) and eliminated in tasks that provided participants with KR about time intervals (i.e., shaping tasks). Previous research in motor learning has suggested that participants base their internal representations on real-time sensory information when they are not provided with KR and that participants do not base their internal representations on real-time sensory information when they are provided with KR. On the other hand, the 1:1 interval-ratio advantage was observed in the current study when participants were provided with KR and also when they were not provided with KR. This finding indicates that the 1:1 advantage may have more than one contributing factor.

In addition, the current study demonstrates that the influence that required time-interval-ratios had on performance in the shaping and imitation tasks was largely independent of other properties of the sets of time intervals that were tested. This is accomplished by showing that the

relations between performance and required time-interval-ratios were similar in two experiments that tested the same time-interval-ratios while using different sets of time interval pairs.

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# Chapter 1. INTRODUCTION

People perform rhythmic movements on a daily basis. Research aimed at understanding how these movements are controlled has led to a fundamental debate regarding the extent to which characteristic movement patterns are a result of perceptual, cognitive, or mechanical properties of the perceptual-motor system. In the context of this debate, the current study advances the argument that representational factors (i.e., cognition and perception) play an important role in the control of rhythmic movements.

In this Introduction I will begin by discussing nonlinear oscillator theory, which posits that the movements people produce are a consequence of biomechanical interactions or dynamics. Then I will review studies that have demonstrated the importance of representational factors in the control of rhythmic movements. I will end the Introduction by previewing the experiments conducted in the current study. These experiments inquired into the nature of the representational factors that influence the control of unimanual finger (single finger) tapping.

## Nonlinear Oscillator Theory

A well known experimental task for studying timing is to have a person move his or her index fingers simultaneously (bimanual movement) back-and-forth together (in-phase) or in opposite directions (anti-phase) (see Kelso, 1981, for a finger oscillation version of the task and see Yamanishi, Kawato, & Suzuki, 1980, for a version of the task where the fingers tap a rigid surface). The in-phase mode of coordination is easier to maintain than the anti-phase mode. This is seen in the greater cycle-to-cycle variability of the relative phase of the two fingers in the anti-phase mode. In addition, it has been shown that when a person is moving in the anti-phase pattern and the speed of a pacing metronome is gradually increased, the person will eventually shift (spontaneously) to the in-phase pattern (this is referred to as a phase transition). However, the opposite pattern of results is not observed. That is, when a person is moving in the in-phase pattern and the speed of a pacing metronome is increased or decreased, the person will not shift to the anti-phase pattern. It has also been shown that anti-phase is a more stable mode of coordination than other relative phases that are intermediate to in-phase and anti-phase (Yamanishi, Kawato, & Suzuki, 1980).

All of these results have been simulated by a mathematical model of two nonlinear oscillators (representing the index fingers) that are nonlinearly coupled (representing the interaction between the movements of the index fingers) (Haken, Kelso, & Bunz, 1985). Taken together, the experimental results and mathematical model demonstrate that two patterns of bimanual finger coordination (graded in terms of stability or difficulty) and a transition between them can be explained by appealing to the nonlinear properties of the neuro-musculo-skeletal system. In other words, pattern difficulty and pattern change are explained within this framework.

In a similar vein, nonlinear oscillator theory has provided an explanatory framework for pattern difficulty and pattern change in a more complex task referred to as bimanual multi-frequency finger tapping (or polyrhythmic finger tapping) (Peper, Beek, & van Wieringen, 1995). In this task, a person moves his or her index fingers at different rates or frequencies specified by a metronome. Certain frequency combinations are easier to produce than others. For example, it is easier to produce a simple 2:1 frequency ratio (faster finger taps twice for every one tap of the slower finger) than a more complex 3:2 frequency ratio (faster finger taps three times for every two taps of the slower finger). In addition it has been shown that when a person is performing a complex frequency ratio, and the speed of a pacing metronome is gradually increased, the person will eventually shift (spontaneously) to producing a simpler frequency ratio.

The levels of frequency-ratio complexity and frequency-ratio transitions are neatly specified by nonlinear oscillator theory and the associated Farey tree (see Figure 1). With respect to multi-frequency finger tapping (as was the case for various phase relations between the fingers), nonlinear oscillator theory explains the difficulty people have in producing various coordination patterns and the transitions that occur between them as emerging from the dynamic properties of the neuro-musculo-skeletal system.

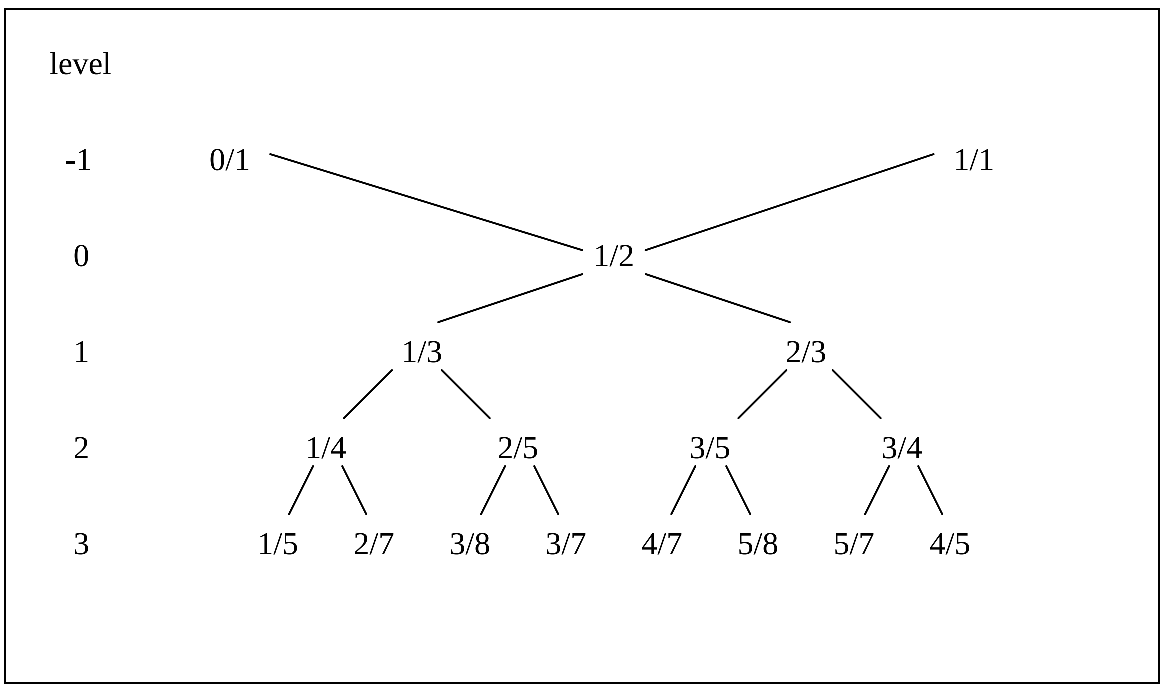



**Figure 1.** The Farey tree. Reproduced from Peper, L. E., Beek, P. J., & van Wieringen, P. (1995). Frequency-induced phase transitions in bimanual tapping. *Biological Cybernetics, 73,* 301-309.

## Representational Accounts of Rhythmic Movement

Much work has also been devoted to providing information-based or representational accounts of performance in bimanual finger tapping. For instance, the *timing control hypothesis* put forth by Semjen and Ivry (2001) posits that performance in both bimanual and unimanual finger tapping is achieved by controlling the time intervals between successive taps. The hypothesis attributes the relative stability of anti-phase bimanual tapping to the equal-duration between-hand inter-tap time-intervals associated with such performance. It has been well established in unimanual finger tapping that equal duration time intervals (isochronous tapping) are easy for people to produce (Semjen & Ivry, 2001; van Donkelaar & Franks, 1991). This is evidenced by the high levels of accuracy (low bias) and consistency (low variability) of the produced time intervals. This is usually demonstrated with a synchronization-continuation task. In this task, participants are asked to tap one finger in a way that imitates the timing of a metronome. At first participants tap in time with external signals (synchronization); then they continue to tap after the external signals stop (continuation). I will also refer to synchronization-continuation tasks as imitation tasks.

Semjen and Ivry (2001) re-conceptualized other relative phases that participants in their bimanual tapping experiments performed in terms of between-hand time-interval sequences. For a subset of relative phase conditions, these authors showed that participants produced a biased relative phase whose time-interval-relation equivalent was approximately 2:1 (the first interval in the sequence was twice as long as the second interval). For example, in the relative phase condition with a time interval relation equal to 7:3, participants tended to produce a time interval relation that approximated 2:1 instead. This latter finding is also a hallmark of unimanual tapping. That is, in imitation tasks, people are also good at unimanually tapping a repetitive two-interval sequence whose durations relate as 2:1 (Essens & Povel, 1985; Povel, 1981; Semjen & Ivry, 2001; Summers, Bell, & Burns, 1989; Summers, Hawkins, & Mayers, 1986). On the other hand, it has been shown that participants are less accurate and more variable when attempting to reproduce interval sequences that relate as 3:1 or 3:2, for example; people tend to reproduce these sequences as approximately 2:1 instead (Povel, 1981). In addition, the 2:1 interval-relation bias has also been demonstrated for unimanual tapping in a different type of task referred to as a grouping task or spontaneous production (Essens & Povel, 1985). In grouping tasks, participants are asked to tap one finger in a way that forms groups of taps (e.g., a group of 2 taps followed by a group of 3 taps). The time intervals participants produce between groups are larger than the time intervals participants produce within groups but, more importantly, the ratios formed by these between-group and within-group time-intervals most often approximate 1:2 or 2:1 (Essens & Povel, 1985).

The demonstration of the 2:1 interval-relation or interval-ratio bias in bimanual tapping is important for the timing control hypothesis because it is not predicted by nonlinear oscillator theory (Semjen & Ivry, 2001). In other words, nonlinear oscillator theory does not predict that people should be biased toward producing the relative-phase equivalent of the 2:1 interval ratio. Instead, as discussed previously, nonlinear oscillator theory predicts that people should be biased toward producing the in-phase and anti-phase relative phases (Haken, Kelso, & Bunz, 1985) which are both the equivalent of the 1:1 interval ratio.

More generally, Semjen and Ivry's (2001) demonstration of similar performances in unimanual and bimanual tapping brings into question the coupled oscillator model of nonlinear oscillator theory (see Summers et al., 1989, for another demonstration of similar time-interval-ratio performances in unimanual and bimanual tapping). In other words, at least two oscillators are required for coupling to be a factor and without additional assumptions it is not obvious why more than a single oscillator would be required for unimanual finger (single finger) tapping. By contrast, a model that controls time intervals between successive taps offers an account of performance for both unimanual and bimanual tapping.

Along similar lines, Summers et al. (1993) proposed that performance in polyrhythmic finger tapping can be explained by an integrated hierarchical process that controls time intervals and has limited attentional resources. As support for this model, Summers et al. (1993) showed that participants' ability to produce various polyrhythms was inversely related to the complexity of the between-hand inter-tap time-interval sequence. This model provides a good example of how observed coordination patterns and associated degrees of difficulty can be explained by positing informational constraints (cognitive constraints). See Deutsch (1983) for an additional representational account of bimanual polyrhythmic finger tapping.

A related study by Klapp et al. (1985) showed that simple rhythms are easier for people to produce than more complex polyrhythms, not only in a bimanual tapping task but also in a unimanual tapping task. Furthermore, these authors showed that participants are quicker to detect the cessation of one of two stimulus sequences when the sequences are related in a simple way than when they constitute a complex polyrhythm. Both of these results are consistent with the idea that representational processes play an important role in multi-frequency finger tapping.

With regard to the studies reviewed thus far, the assertion that representational factors (i.e., cognition and perception) play an important role in controlling rhythmic movements was based on demonstrations that performance biases did not depend on the effector or combination of effectors that were used to produce the movements (Klapp et al., 1985; Semjen & Ivry, 2001;

Summers et al., 1989). Therefore, these studies can be seen as providing indirect support for the notion that representational factors play an important role in controlling rhythmic movements.

The role of representational factors in the control of rhythmic movements has been further explored in experiments that modified the prototypical tasks (introduced above) in some way without changing, or making minimal changes to, the required movements. Because the experimental manipulations in these studies were designed to influence representational processes, they can be seen as providing direct support for the idea that representational factors play an important role in controlling rhythmic movements. For instance, in a bimanual finger oscillation task, Zanone and Kelso (1992) allowed participants to practice a 90° phase relation extensively and provided them with knowledge of results after each trial. Under these circumstances, it was shown that people could learn to produce the 90° phase relation -- a phase relation that, by definition, is halfway between, and so as different as possible from, phase relations of 0° (in-phase) and 180° (anti-phase). Similarly, Swinnen et al. (1997) showed that people can learn to oscillate their upper-limbs in a 90° phase relation when provided with extensive practice. These authors also showed that learning was greatest when participants were provided with augmented performance feedback. Such demonstrations of learning highlight the importance of information -- gained from knowledge of results or during the natural course of practice -- for controlling rhythmic movements.

Additional work has further advanced our understanding of the locus within the perceptual-motor system of the previously-discussed bimanual coordination effects. It has been shown (Mechsner et al., 2001) that the degree of difficulty of various bimanual coordination tasks can be attributed to perceptual factors. For instance, Mechsner et al. (2001) showed that oscillating one’s fingers in a mirror-symmetrical fashion (moving both fingers towards and away from the body's midline simultaneously) or in-phase is more stable than oscillating them in parallel (moving one finger away from the body's midline and the other finger toward the midline) or anti-phase regardless of whether homologous or non-homologous muscles were used to make the movements.[1] Mechsner et al. (2001) took this result to suggest that the visuo-spatial relation between the two fingers is a prominent control factor. As further support for the importance of visual information in the control of movement, Mechsner et al. (2001) showed that complex frequency ratios (e.g., 4:3) for two-hand cranking can be performed easily if, via a system of gears connecting the cranks to seen flags, the perceptual consequences of the motions are reduced to simple ratios (e.g., 1:1).

Other research has demonstrated the importance of cognitive factors such as planning in bimanual coordination. In this connection, Rosenbaum, Dawson, and Challis (2006) showed that people can generate two-hand oscillations virtually perfectly at any frequency ratio (e.g., 4:3) if the hands maintain light touch on two moving objects, thereby letting touch relieve high-level movement planning. In much the same spirit, Franz et al. (2001) showed that arching movements made by the two hands in the frontal plane can either be performed easily or with considerable difficulty depending on how well the two movements are mentally represented.

Further support for the importance of representational factors in controlling rhythmic movements has been obtained in the domain of unimanual finger tapping. For instance, it has been shown that the difficulties participants experience in unimanually producing time-interval sequences that do not relate as 1:1 or 1:2 (e.g., 1:3 or 1:4) can be overcome when these sequences are embedded in larger sequences with metrical structure such as 1:1:1:3 or 1:1:1:1:4 (Essens & Povel, 1985; Povel, 1981; Summers, Hawkins, & Mayers, 1986; van Donkelaar &

[1] This manipulation was achieved by requiring participants to hold their hands in a congruous position (both hands either palm-down or palm-up) or an incongruous position (one hand palm-down and the other hand palm-up) while oscillating their fingers.

Franks, 1991). Therefore, with the aid of metrical structure, participants were able to accurately reproduce temporal sequences that they were otherwise unable to reproduce. This result was taken to suggest that the difficulties people had in reproducing certain interval ratios (e.g., 1:3 or 1:4) were perceptually and cognitively mediated (Povel, 1981).

In addition, Collier and Wright (1995) showed that three musicians (two were highly trained), provided with ample practice and knowledge of results, could tap repetitive two-interval sequences whose durations related as 3:2, 3:1, 4:1, and 2:1 equally well. Furthermore, although the musicians performed more complex interval ratios (i.e., 1.82:1, 2.72:1, and 3.33:1) less well than the simpler ratios, their performance of the complex ratios improved over blocks of trials (Collier & Wright, 1995).[2] In a similar vein, van Donkelaar and Franks (1991, Experiment 1) showed that by providing people with a considerable amount of practice and knowledge of results, a three interval sequence (i.e., 2:2:3) with an embedded 2:3 ratio could be performed as well as a three interval sequence (i.e., 1:1:2) with an embedded 1:2 ratio.

Finally, Summers et al. (1986) showed differences between the time-interval-ratio biases for unimanual tapping in an imitation task and in a production task that presented the target interval ratios to participants as a sequence of numbers on a card (e.g., “1:2” or “1:3”). For example, the authors showed the 1:2 interval-ratio bias in the imitation task, but not in the production task. Rather, in the production task, participants produced an average ratio of approximately 1:2.4 in the 1:2 target-ratio condition. The authors suggested that the performance differences may have been due to different internal representations or different strategies that may have accompanied performance in the two tasks.

[2] Collier and Wright (1995) used a bimanual tapping task that required participants to synchronize the taps of the left and right fingers for all interval-ratio conditions.

## Preview of Current Study

The study by Summers et al. (1986) is representative of the approach taken in the current study. The basic idea is that it is plausible that different methods for inducing motor output (e.g., imitation task versus production task) engage various information processes (e.g., short-term memory, long-term memory, decision processes, etc.) to different degrees. The information processes that are thought to be engaged by a particular method for inducing motor output can then be related to performance. Therefore, in the current study, I tested hypotheses about the type of representational processes that contribute to the 1:1, 1:2, and 2:1 interval-ratio advantages by varying the method used to induce motor output while holding the effector that participants used constant (i.e., all tasks involved unimanual finger tapping).

The first question I addressed was whether the 1:1, 1:2, and 2:1 interval-ratio advantages in unimanual tapping are a reflection of perceptual biases. More specifically, I asked whether these advantages can be linked to internal representations based on real-time sensory events associated with target performance. In other words, are the 1:1, 1:2, and 2:1 interval-ratio advantages a reflection of how tapping sounds, looks, and or feels? I decided to address this question because even though previous studies (Semjen & Ivry, 2001; Summers et al., 1989) have suggested that the source of the 1:1, 1:2, and 2:1 interval-ratio advantages is representational in nature (as opposed to biomechanical), precise information regarding the nature of the representations was lacking.

Research that has focused on how participants' ability to learn new motor patterns is influenced by knowledge of results suggested a way of addressing this question. Knowledge of results (KR) is information about the outcome of a response that is provided in addition to feedback that is naturally received when a response is made (Salmoni, Schmidt, & Walter, 1984).

For example, in a finger-tapping task KR could be provided about the time intervals between successive taps. In addition, participants would naturally receive kinesthetic feedback during finger tapping and possibly auditory and visual feedback. It has been shown that KR helps participants accurately produce target movement patterns (Salmoni, Schmidt, & Walter, 1984; Winstein, 1991; Wulf & Schmidt, 1989). However, when KR is subsequently removed, performance has been shown to deteriorate (Salmoni, Schmidt, & Walter, 1984; Winstein, 1991; Wulf & Schmidt, 1989). This pattern of results has been explained by the idea that participants develop internal representations by focusing on the relation between KR and their motor performance to such an extent that they do relatively little processing or encoding of the kinesthetic, auditory, and visual feedback that accompanies motor performance (Salmoni, Schmidt, & Walter, 1984; Winstein, 1991; Wulf & Schmidt, 1989). Consequently, participants perform well as long as KR is available. However, when KR is removed, participants are left without a well-defined frame of reference for target performance and performance deteriorates. Therefore, this motor-learning work has suggested that when KR is available, participants do not base their internal representations on the real-time sensory information that accompanies their motor performance. By contrast, this work has also suggested that when KR is not available, participants do base their internal representations on such sensory information.

In considering the aforementioned experimental conditions (i.e., KR versus no KR) and the types of internal representations they are thought to invoke, the fact that most tasks that have demonstrated the 1:1, 1:2, and 2:1 interval-ratio advantages have not provided participants with KR (e.g., imitation tasks and grouping tasks) is consistent with the hypothesis that the source of the advantages was internal representations based on real-time sensory information. In imitation tasks the idea is that participants based their internal representations on real-time sensory information from the metronome and also from their finger tapping. Similarly, for grouping tasks the idea is that participants based their internal representations on real-time sensory information from their finger tapping alone (grouping tasks do not employ a metronome).

In the current study, I set out to demonstrate that the 1:1, 1:2, and 2:1 interval-ratio advantages were eliminated in unimanual tapping tasks that provided participants with KR. Based on the type of internal representation thought to be invoked by KR, such a demonstration would also be consistent with the hypothesis that the source of the 1:1, 1:2, and 2:1 interval-ratio advantages is internal representations based on real-time sensory information.

I tested this hypothesis in Experiment 1 by having participants attempt to discover the required sequence through a trial-and-error shaping procedure during which the participants were provided with KR for individual time intervals. I found that participants were no better at producing sequences comprising simpler interval ratios (e.g., 2:1) than complex ratios (e.g., 7:5), though 1:1 ratios were clearly best. This outcome supports the hypothesis that the source of the 1:2 and 2:1 interval-ratio advantages is internal representations based on real-time sensory events. On the other hand, the hypothesis was not supported for 1:1 interval ratios. Based on this outcome, I concluded that the 1:1 advantage is not simply due to some special benefit ascribable to real-time perceptual information. For instance, the 1:1 advantage may also derive from cognitive efficiencies associated with replicating a single time interval rather than producing two different time intervals, as required for all other interval ratios.

In Experiment 2, I used a combined shaping and continuation procedure. In this task participants attempted to discover the required sequence through a trial-and-error shaping procedure during which they were provided with KR for individual time intervals. In later trials the KR was removed and participants attempted to continue producing the timing from previous trials. The idea was that when KR was available, participants would base their internal representations on it instead of the real-time sensory events that accompanied their tapping. Therefore, if such sensory information is the source of the 1:2 and 2:1 interval-ratio advantages, these advantages should be eliminated when KR is available. By contrast, the idea was that when KR was no longer available, participants would base their internal representations on the real-time sensory events that accompanied their tapping. Therefore, if such sensory information is the source of the 1:2 and 2:1 interval-ratio advantages, these advantages should be observed when KR is no longer available. In accord with the predictions I found 1:2 and 2:1 advantages when KR was not available to participants (i.e., continuation phase). However, contrary to the predictions I also found evidence of 1:2 and 2:1 advantages when KR was available to participants (i.e., shaping phase). It is concluded that the source of the 1:2 and 2:1 advantages during shaping (KR available) may have been that participants processed the real-time sensory events that accompanied their tapping during that phase in an attempt to develop a frame of reference for the upcoming continuation phase (KR unavailable).

In Experiment 3, I had participants perform in a shaping task and an imitation task. The shaping procedure was the same as in Experiment 1 (i.e., KR for individual time intervals available after every trial). The imitation task required participants to listen to a sequence of clicks generated by a computer. Participants then reproduced the timing of the clicks by pressing a spacebar that also generated clicking sounds. KR was not provided to participants during the imitation task. The idea was that in the imitation task participants would base their internal representations on real-time sensory events (e.g., the sequence of clicks generated by the computer and their finger taps). To the contrary, the idea was that in the shaping task participants would base their internal representations on the KR. Therefore, if the source of the 1:2 and 2:1

interval-ratio advantages is real-time sensory information, then these advantages should be eliminated in the shaping task and observed in the imitation task. The results matched these predictions.

The second question I addressed was whether the relations between performance and required time-interval-ratios for the shaping and imitation tasks were independent of other properties of a set of time intervals. I tested this by comparing performance between the shaping tasks and imitation tasks of Experiments 3 and 4. These experiments tested the same time interval ratios while using different sets of time interval pairs. The time interval pairs differed in terms of the intervals themselves and also in terms of the rules that were used to generate the interval pairs. The differences between the rules that were used to generate the sets of time interval pairs in Experiments 3 and 4 are discussed in more detail in the method section of Experiment 4. I reasoned that if the relations between performance and required time-interval-ratios were independent of other properties of a set of time intervals, then the relations should be similar for Experiments 3 and 4. The results of Experiments 3 and 4 were consistent with the hypothesis. Even though the two experiments tested different sets of time interval pairs, the relations between performance and required time-interval-ratios were similar for the shaping tasks of Experiments 3 and 4 and also for the imitation tasks of Experiments 3 and 4.

A third and final question that I asked was whether the reason KR eliminated the 1:2 and 2:1 interval-ratio advantages in Experiments 1, 3, and 4 was that it focused participants' attention on the time intervals themselves and not on the relation between the time intervals. If the time intervals were represented independently, there is no reason to suspect that the relation between intervals (i.e., time ratio) should influence performance. Experiments 5 and 6 were designed to address this alternative interpretation of the results of Experiments 1, 3, and 4.

In Experiment 5, I employed a trial-and-error unimanual tapping procedure that provided participants with KR after each trial. However, instead of providing KR for individual time intervals, I provided participants with KR for the ratio formed by adjacent time intervals (i.e., time interval 2 divided by time interval 1). I reasoned that providing participants with KR in terms of time ratios would focus their attention on the relation between the time intervals in addition to the time intervals themselves. Therefore, if the 1:2 and 2:1 advantages were eliminated in the shaping tasks of Experiments 1, 3, and 4 because the KR focused participants' attention on the time intervals and not on the relation between the time intervals, then it is reasonable to expect to see the 1:2 and 2:1 advantages in Experiment 5. This is because Experiment 5 was designed to focus participants' attention on the relation between the time intervals. However, I obtained no evidence that 1:2 or 2:1 time ratios were easier to perform than the more complex ratios. This outcome is not consistent with the hypothesis that KR eliminates the 1:2 and 2:1 advantages by focusing participants' attention on the time intervals themselves and not on the relation between the time intervals. Finally, a number of differences between the procedures used in Experiment 5 on the one hand and Experiments 1, 3, and 4 on the other hand are discussed in terms of how they may have influenced the results of Experiment 5. These differences were in addition to whether KR was presented in terms of time intervals or time ratios.

Experiment 6 was designed to provide a more direct test of the hypothesis that the reason KR eliminated the 1:2 and 2:1 interval-ratio advantages in Experiments 1, 3, and 4 was that it focused participants' attention on the time intervals themselves and not on the relation between the time intervals. In Experiment 6 participants performed in a shaping task in which they were provided with KR for the ratio formed by adjacent time intervals (i.e., time interval 2 divided by time interval 1). However, in this task I also placed upper and lower limits on the time intervals that participants were allowed to produce (i.e., 300 and 1100 milliseconds). In addition, participants performed in an imitation task identical to the imitation task of Experiment 3. I reasoned that if the 1:2 and 2:1 advantages were eliminated in the shaping tasks of Experiments 1, 3, and 4 because the KR focused participants' attention on the time intervals themselves, then the 1:2 and 2:1 advantages should be observed in the shaping task of Experiment 6. This is because the KR in Experiment 6 was designed to focus participants' attention on the relation between time intervals in addition to the time intervals themselves. I also reasoned that due to the absence of KR, participants in the imitation task may naturally represent the relation between time intervals in addition to the time intervals themselves. I found 1:2 and 2:1 advantages for the imitation task of Experiment 6 but not the shaping task. The absence of 1:2 and 2:1 advantages in the shaping task is not consistent with the hypothesis that KR eliminates the 1:2 and 2:1 advantages by focusing participants' attention on the time intervals themselves and not on the relation between the time intervals. If this were the case, it would be reasonable to have expected to see the 1:2 and 2:1 advantages in the shaping task of Experiment 6.

In the following, I will present in more detail the experiments mentioned above. In these experiments I addressed the following three primary questions regarding the nature of the representational processes involved in unimanual finger tapping. The first question was whether the 1:1, 1:2, and 2:1 interval-ratio advantages in unimanual tapping are a reflection of internal representations based on real-time sensory events associated with target performance. The second question was whether the relations between required time-interval-ratios and performance for shaping and imitation tasks are independent of other properties of a set of time interval pairs (i.e., the intervals themselves and the rules used to generate the interval pairs). The third question was whether KR eliminates the 1:2 and 2:1 interval-ratio advantages by focusing participants' attention on the time intervals themselves and not on the relation between the time intervals.

## Chapter 2. EXPERIMENT 1

This experiment was designed to test the hypothesis that the source of the 1:1, 1:2, and 2:1 interval-ratio advantages observed in previous studies of unimanual tapping (i.e., imitation tasks and grouping tasks) was internal representations based on real-time sensory events associated with target performance. I reasoned that if this hypothesis were true, these advantages should be eliminated in a tapping experiment that provides participants with KR. This is because previous research (Salmoni, Schmidt, & Walter, 1984; Winstein, 1991; Wulf & Schmidt, 1989) has suggested that when KR is available, participants do not base their internal representations on real-time sensory information.

### Method

*Participants*

Twenty-five healthy Penn State undergraduates participated for course credit. Fourteen were female and eleven were male. Twenty-two participants were right-handed, two were left-handed, and one was ambidextrous. Participants reported musical training that ranged from no training whatsoever to eight years training on a musical instrument. All participants were naive to the hypotheses.

*Apparatus*

Participants sat eye level with a Dell Ultrasharp 17 inch flat panel monitor (1280 x 1024 pixels) set 20 inches away on the desk. The experiment was conducted in a MATLAB-based environment on a Dell OptiPlex GX620 computer. Participants responded on a Dell RT7D50 keyboard.

*Procedure and Design*

For a given target sequence, a participant completed 42 trials. The sequence of events for an individual trial is shown in Figure 2. The participant saw three open circles arrayed horizontally on a computer screen. Whenever the participant wished (i.e., with no time pressure to start), s/he produced two successive time intervals by pressing the computer spacebar three times with the index finger of his or her dominant hand. When the spacebar was pressed for the first time, the left circle was immediately filled in. When the spacebar was pressed for the second time, nothing changed on the screen. When the spacebar was pressed for the third time, visual feedback (KR) was given both about the first produced interval (the time between the first press and the second) and the second produced interval (the time between the second press and the third). The feedback about the first interval was associated with the middle circle. The feedback about the second interval was associated with the right circle. The feedback about time intervals remained on the computer screen for one second.

There were three possible forms of visual feedback for each interval. If the produced interval fell within a currently prescribed accuracy band, a blue dot filled the corresponding circle. If the produced interval was too long relative to the currently prescribed accuracy band, a line of fixed length extended up from the corresponding circle. If the produced interval was too short relative to the currently prescribed accuracy band, a line of fixed length extended down from the corresponding circle. Because the length of the line was fixed, its length provided no information about the extent of overshoot or undershoot. The accuracy band for an interval started at ±12.66% of each target interval. If a participant achieved correct trials on at least 2 out of 3 consecutive trials, the accuracy bands of both intervals were reduced by 25%. These values were arrived at in pilot work.

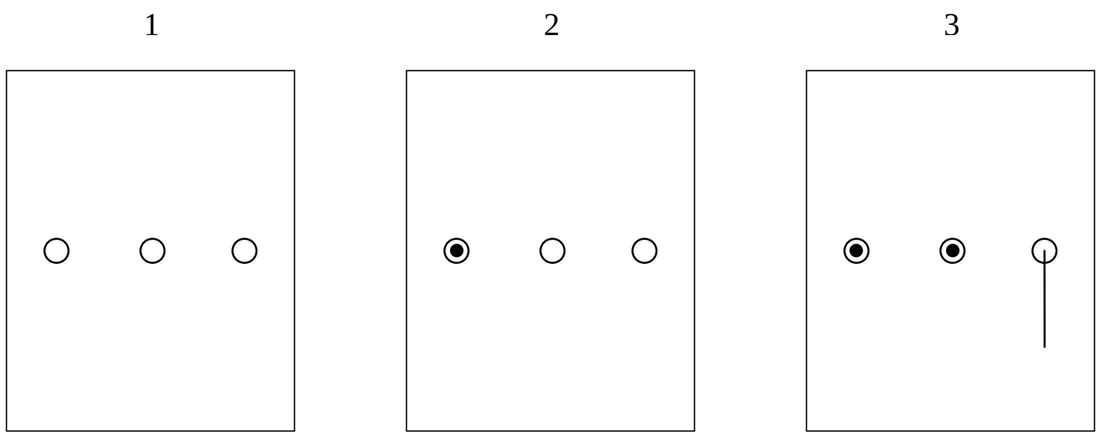



**Figure 2.** Feedback display for Experiment 1, Phase 1 of Experiment 2 (after trials 1-22), and the shaping tasks of Experiments 3 and 4. **(1)** Initial screen appears 1 sec after completion of previous trial. **(2)** Participant begins timing interval 1 by pressing the spacebar, whereupon a green dot appears. A second spacebar-press completes interval 1 and begins interval 2, and a third spacebar-press completes interval 2. **(3)** After completion of interval 2, feedback is shown at center and right for intervals 1 and 2, respectively. The feedback shown here indicates that interval 1 was correct but interval 2 was too short.

Participants were instructed to get as many trials correct as possible in a block of trials. A trial was considered correct if intervals 1 and 2 both got blue dots. After a participant completed 42 trials, s/he was given end-of-block feedback regarding the number of correct trials for that block. The participant was also reminded of his or her best score (i.e., the highest number of correct trials for a previous block). The end-of-block feedback took the form of numbers on the computer screen.

In addition, participants were asked to keep the index finger in contact with the spacebar when pressing it and to minimize extraneous movements. This was done to keep the physical features of the task similar across participants.

Each participant completed nine blocks of trials, with each block involving a unique pair of target times from the set {350, 500, 700 ms}. The pairs (and their ratios) were as follows:

| | |
|---|---|
| 350-350 | (1:1) |
| 350-500 | (7:10) |
| 350-700 | (1:2) |
| 500-350 | (10:7) |
| 500-500 | (1:1) |
| 500-700 | (5:7) |
| 700-350 | (2:1) |
| 700-500 | (7:5) |
| 700-700 | (1:1) |

Each participant was randomly assigned three of the nine interval pairs for practice. Approximately five trials were completed for each of the three practice blocks. In the experiment, the full set of nine interval pairs were presented to each participant in a different random order for each participant.

*Data Analysis*

Performance was analyzed in two ways -- in terms of how accurately participants produced the target intervals and in terms of how accurately participants produced the ratios formed by the target intervals. I analyzed the data both ways because inaccurate production of intervals relative to their target values did not necessarily imply inaccurate production of the needed ratio.

The way I analyzed <u>time intervals</u> was to assess the probability that both intervals produced in the trials of a block fell within ±8.39% of their respective target intervals. This percentage ensured that the allowable ranges for different target intervals did not overlap. The resulting interval ranges were

{321  350  379}

{458  500  542}

{641  700  759}.

I defined the time ratio as interval 2 divided by interval 1. I analyzed the <u>time ratios</u> by calculating the probability that the ratios produced in the trials of a block fell within −15.48% to +18.32% of the ratio formed by the relevant target interval pair. These percentages were derived from the upper and lower limits of the allowable ranges associated with the target interval pairs. The allowable ranges for the ratios formed by the different target interval pairs did not overlap.

The reason I chose to use the categorical measures of error is that they reduce the chances of giving an undue advantage to time ratios that may have been difficult to produce but were near a preferred ratio (e.g., 1.25:1 is near 1:1). A continuous measure of error (e.g., constant error) would not have controlled for such undue advantages. See Drake and Gerard (1989) for another example of a unimanual tapping study that used categorical measures of error to assess time interval and time ratio performance.

For purposes of data analysis, I placed the nine target interval pairs into three groups: (a) the 1:1 pairs (350-350 ms, 500-500 ms, 700-700 ms); (b) the 1:2 and 2:1 pairs (350-700 ms and 700-350 ms); and (c) the complex pairs (500-700 ms, 700-500 ms, 350-500 ms, and 500-350 ms).

For each group of interval pairs, I calculated each participant's probability of success, averaged across trials 24 through 42, for producing the target interval pairs and for producing the associated ratios. I chose to analyze average performance for the last 19 trials in each block of trials (i.e., trials 24 to 42) because I thought the effects of shaping would be most apparent in these later trials.

In addition, for each target interval pair, I calculated each participant's median produced time interval 1, median produced time interval 2, and median produced time ratio (interval 2 divided by interval 1), across trials 24 through 42.

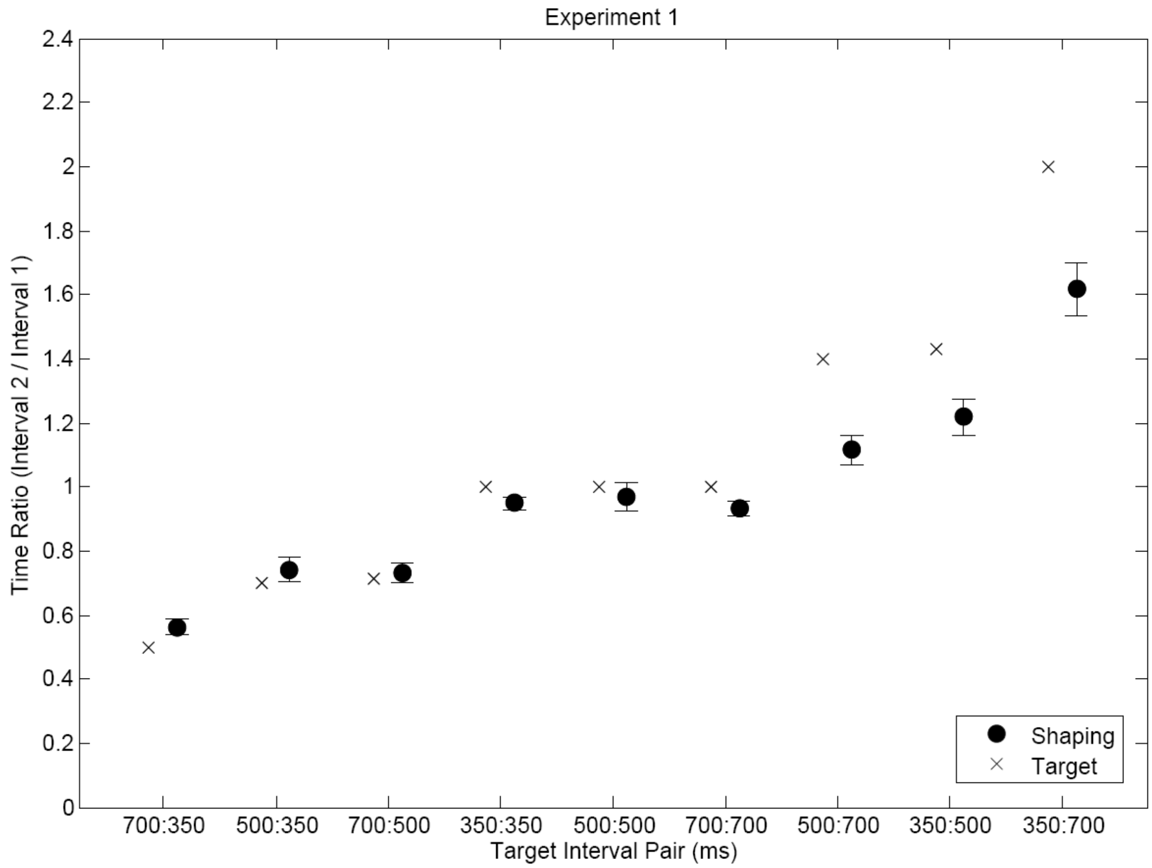
## Results

The median produced time intervals 1 and 2, across trials 24 through 42, and the target interval pairs are shown in Table 1. In addition, the median produced time ratios, across trials 24 through 42, and the time ratios formed by the target interval pairs are shown in Figure 3.

Table 1

*Experiment 1 -- Group Means (SD) of Median Produced Time Intervals for Trials 24 to 42*

| Target Interval Pair (ms) | Produced Intervals (ms) | |
|---|---|---|
| Interval 1:Interval 2 | Interval 1 | Interval 2 |
| 350:350 | 358 (15) | 346 (35) |
| 500:500 | 497 (38) | 478 (85) |
| 700:700 | 668 (68) | 623 (108) |
| 350:700 | 391 (53) | 615 (132) |
| 700:350 | 693 (78) | 379 (83) |
| 500:700 | 537 (41) | 580 (111) |
| 700:500 | 682 (76) | 488 (76) |
| 350:500 | 377 (35) | 453 (79) |
| 500:350 | 507 (59) | 369 (79) |




| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Ratio: | .50 .56 | .70 .74 | .71 .73 | 1.00 .95 | 1.00 .97 | 1.00 .93 | 1.40 1.12 | 1.43 1.22 | 2.00 1.62 |

**Figure 3.** Median produced time ratios, across trials 24 through 42, and the time ratios formed by the target interval pairs of Experiment 1. Black crosses represent the time ratios formed by the target interval pairs. Black dots represent the means of the median produced time ratios for the shaping task. Vertical bars denote ±1 standard error of the mean. In addition, the time ratios formed by the target interval pairs and the mean produced time ratios for the shaping task are displayed below and to the left and right respectively of the corresponding target interval pair on the x-axis of the graph.

Figure 4 shows the probability of accurately producing the time intervals and of accurately producing the time ratios, averaged over participants for each of the three groups of interval pairs. Produced time intervals were considered accurate or correct if both time intervals in a pair fell within ±8.39% of their respective target intervals. A produced time ratio was considered accurate or correct if it fell within −15.48% to +18.32% of the ratio formed by the relevant target interval pair. The average points were fitted by power functions that characterized the increase in the probability of successful performance over practice (i.e., as a function of trial) for all groups of interval pairs.[3]

In the analyses of time interval performance and time ratio performance that follow, I treated the three groups of interval pairs (i.e., 1:1 pairs, 1:2 and 2:1 pairs, and complex pairs) as three experimental conditions. This simplification was justified by confirming, via Tukey's Honestly Significant Difference method, that there were significant differences between the three groups but never within any of the three groups, with all *p* values exceeding .10 for the latter tests. I analyzed the probabilities of producing the target interval pairs, averaged across trials 24 through 42, with interval-pair group as the within-participants factor, and, in a second ANOVA, the probabilities of producing the ratios formed by the target interval pairs, with the same design.

[3] In trial 2, the average probability of accurately producing the time interval pairs of the 1:2 and 2:1 interval-pair group was zero. The power function was not fit to this data point for the 1:2 and 2:1 group.

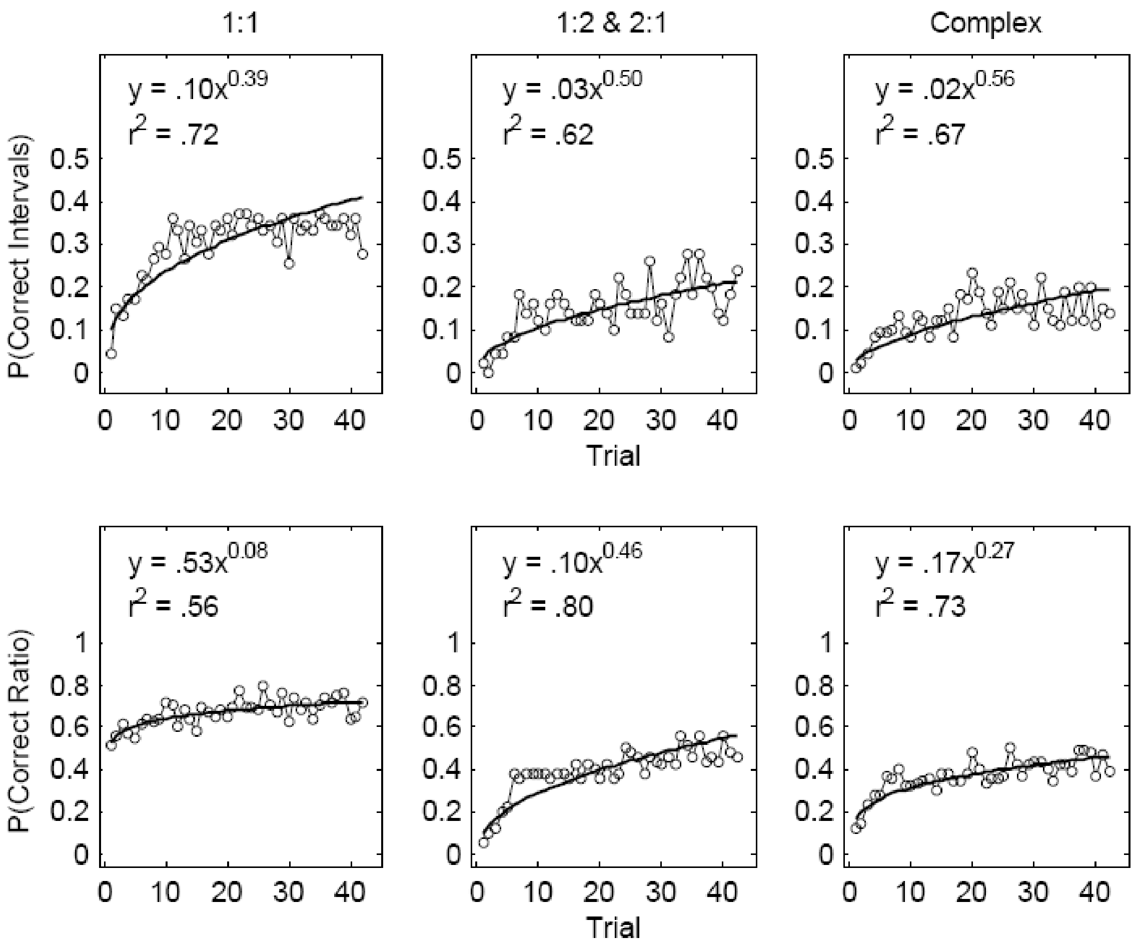



**Figure 4.** Probability of producing the target interval pairs (**top**) and probability of producing the ratios formed by the target interval pairs (**bottom**) averaged over participants for the three groups of interval pairs of Experiment 1. Power functions are fitted to all trials (i.e., trials 1 to 42).

I found a statistically significant main effect of interval-pair group for time intervals, $F(2, 48) = 19.34$, $p < .01$, and time ratios, $F(2, 48) = 21.96$, $p < .01$. The results of two Tukey's HSD Tests showed that: (a) the probability of success in the 1:2 and 2:1 conditions was significantly less than in the 1:1 conditions for time intervals and time ratios, *ps* < .01; (b) the probability of success in the complex conditions (i.e., 5:7, 7:5, 7:10, and 10:7) was significantly less than in the 1:1 conditions for time intervals and time ratios, *ps* < .01; and (c) the probability of success in the complex conditions was not significantly less than in the 1:2 and 2:1 conditions for time intervals and time ratios, *ps* > .10. These results indicate that participants produced time intervals and time ratios more accurately in the 1:1 conditions than in the 1:2, 2:1, and complex conditions, but participants did not produce time intervals or time ratios more accurately in the 1:2 and 2:1 conditions than in the complex conditions.

One concern about these results is that the findings may have reflected unequal numbers of trials in the three groupings. To check this, I re-ran each ANOVA (and accompanying Tukey's HSD Tests) using the first two blocks of trials of the 1:1, 1:2 and 2:1, and complex-ratios conditions. These two analyses led to the same conclusions.

## Discussion

Previous research on motor timing has indicated that 1:1, 1:2, and 2:1 time ratios enjoy special status (Essens & Povel, 1985; Povel, 1981; Semjen & Ivry, 2001; Summers et al., 1986; Summers, Bell, & Burns, 1989). The results of the shaping task used here also indicate that 1:1 time ratios were special. However, I obtained no evidence that 1:2 or 2:1 time ratios were easier to perform than the more complex ratios.

The fact that the 1:1 time-ratio advantage was not eliminated with the present shaping procedure points to the robustness of this advantage. The present finding that 1:1 time ratios are special is reminiscent of work by Jones and Wearden (2004), who showed that participants performed better in a time perception task when they had to remember only one standard time interval than when they had to remember two standard time intervals. A related finding was obtained by van Donkelaar and Franks (1991, Experiment 2), who found that reaction times to produce sequences containing 1:1 time ratios were shorter than reaction times to produce sequences containing 1:2 or 2:3 time ratios, although the latter time ratios did not have different reaction times. van Donkelaar and Franks (1991) remarked that a 1:1 time ratio has a different "general structure" (i.e., one time interval twice) than all other ratios (i.e., two different time intervals) and that this has the largest impact on performance.

The present finding that participants performed equally well in the 1:2, 2:1, and complex conditions in the context of the shaping procedure is consistent with the hypothesis that the source of the 1:2 and 2:1 interval-ratio advantages observed in previous studies (i.e., imitation tasks and grouping tasks) was internal representations based on real-time sensory information. The idea is that in the shaping procedure participants focused on the KR to such an extent that they did relatively little processing of the sensory information that accompanied their finger tapping.

An alternative interpretation of the present results points to the fact that the trials in the task used here were discrete or separated by visual feedback (KR) whereas most previous studies that used either imitation tasks or grouping tasks employed continuous tapping designs. In other words, the present shaping task imposed a minimum inter-trial interval during the presentation of feedback, whereas previous studies used continuous tapping, which can be seen as a task with an inter-trial interval of 0 s. It is possible that this feature of the task allowed my participants to do more planning of the two forthcoming intervals than was possible otherwise, and this increased planning may have played a role in eliminating the 1:2 and 2:1 advantages in the shaping task.

As discussed later, Experiment 3 was designed in part to address the two alternative interpretations of the results of Experiment 1. Experiment 3 tested for the 1:2 and 2:1 advantages in a discrete-trial imitation task and a shaping task identical to the one used in Experiment 1. By using a discrete-trial tapping procedure for both tasks, any differences in performance could be more closely associated with the imitation and shaping procedures.

## Chapter 3. EXPERIMENT 2

Having demonstrated that the 1:2 and 2:1 interval-ratio advantages were eliminated in a shaping task that provided participants with KR, I asked in the second experiment whether the 1:2 and 2:1 advantages would be observed in a subsequent phase of the experiment in which KR was removed.

To pursue this possibility in Experiment 2, I combined the use of shaping with the use of continuation. Whereas previous studies had participants synchronize taps with external signals and then continue without those external signals, in Experiment 2 I provided participants with visual end-of-trial feedback (KR), as in the first experiment, but then I had them continue, in later trials, without such visual feedback.

I reasoned that if the source of the 1:2 and 2:1 interval-ratio advantages is internal representations based on real-time sensory information, then these advantages should be eliminated in the shaping phase (KR is provided) and observed in the continuation phase (KR is not provided). These predictions were based on previous research (Salmoni, Schmidt, & Walter, 1984; Winstein, 1991; Wulf & Schmidt, 1989) that has suggested that participants base their internal representations on real-time sensory information when KR is not provided to them and that participants do not base their internal representations on real-time sensory information when KR is provided to them.

### Method

*Participants*

Thirty healthy Penn State undergraduates (24 female and 6 male) participated for course credit. Twenty-eight participants were right-handed and two were left-handed. Participants reported musical training that ranged from no training whatsoever to eight years training on a musical instrument. All participants were naive to the hypotheses, and none had been in Experiment 1.

*Apparatus*

The apparatus was the same as in Experiment 1.

*Procedure and Design*

As in Experiment 1, I asked participants to keep their index finger in contact with the spacebar when pressing it and to minimize extraneous movements. This was done in order to keep the physical features of the task similar across participants.

For a given target sequence, a participant completed 44 trials. The sequence of events for Phase 1 trials (trials 1-22) was identical to the sequence of events in all trials in Experiment 1 (see Figure 2). However, during Phase 2 (trials 23-44), participants were given uninformative feedback after each trial. Here they were shown a blend of all the visual feedback possibilities in Phase 1 (i.e., a blue dot, a blue bar of fixed length above the middle and right circle, and a blue bar of fixed length below the middle and right circle) no matter what time intervals they produced. Participants were told, for Phase 2, to continue producing the time intervals they had been producing for Phase 1. After participants completed the 44 trials in a block, they were given end-of-block feedback for Phase 1 and Phase 2 separately. Thus, they were shown the number of correct trials and their best score so far (in terms of number of correct trials) for Phase 1 and the number of correct trials and their best score so far (in terms of number of correct trials) for Phase 2. In Phase 2, a trial was considered correct if the produced time intervals were within their respective minimum accuracy-bands established at the end of Phase 1.

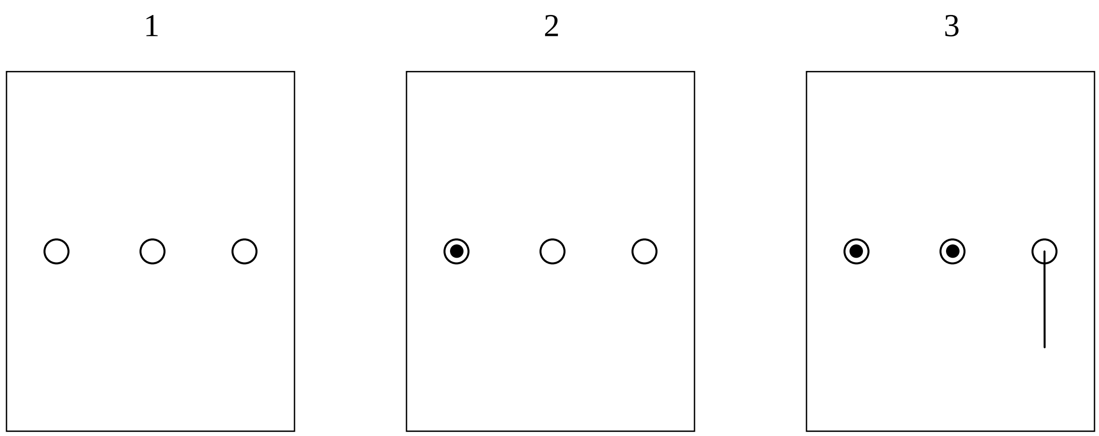



**Figure 2.** Feedback display for Experiment 1, Phase 1 of Experiment 2 (after trials 1-22), and the shaping tasks of Experiments 3 and 4. **(1)** Initial screen appears 1 sec after completion of previous trial. **(2)** Participant begins timing interval 1 by pressing the spacebar, whereupon a green dot appears. A second spacebar-press completes interval 1 and begins interval 2, and a third spacebar-press completes interval 2. **(3)** After completion of interval 2, feedback is shown at center and right for intervals 1 and 2, respectively. The feedback shown here indicates that interval 1 was correct but interval 2 was too short.

During the experiment, each participant completed nine blocks of trials, with each block testing a unique pair of target time intervals. The target time interval pairs were those tested in Experiment 1. Each participant was randomly assigned three of the nine interval pairs for practice. Approximately ten Phase 1 and ten Phase 2 trials were completed for each of the three practice blocks. In the experiment, the full set of nine interval pairs were presented to each participant in a different random order for each participant.

*Data Analysis*

I calculated the probability of producing the target interval pairs and the ratios formed by the target interval pairs using the same accuracy criteria as in Experiment 1 and using the same three groupings.

The way I analyzed time intervals was to assess the probability that both intervals produced in the trials of a block fell within ±8.39% of their respective target intervals. This percentage ensured that the allowable ranges for different target intervals did not overlap.

I defined the time ratio as interval 2 divided by interval 1. I analyzed the time ratios by calculating the probability that the ratios produced in the trials of a block fell within −15.48% to +18.32% of the ratio formed by the relevant target interval pair. These percentages were derived from the upper and lower limits of the allowable ranges associated with the target interval pairs. The allowable ranges for the ratios formed by the different target interval pairs did not overlap.

For purposes of data analysis, I placed the nine target interval pairs into three groups: (a) the 1:1 pairs (350-350 ms, 500-500 ms, 700-700 ms); (b) the 1:2 and 2:1 pairs (350-700 ms and 700-350 ms); and (c) the complex pairs (500-700 ms, 700-500 ms, 350-500 ms, and 500-350 ms).

For each of the three groupings, I calculated each participant's probability of success, averaged across trials 14 through 23 and averaged across trials 24 through 42, both for the probability of producing the target interval pairs and for the probability of producing the associated ratios. I chose to analyze average performance for the last 10 trials of Phase 1 (i.e., trials 14 to 23) in each block of trials because I reasoned that the effects of shaping should be most apparent toward the end of Phase 1. I analyzed trials 24 to 42 to assess Phase 2 performance. I omitted trials 43 and 44 from this analysis so the analysis of Phase 2 covered the same trials as the previous analysis of Experiment 1 (Experiment 1 had 42 trials per block whereas Experiment 2 had 44 trials per block).

In addition, for each target interval pair, I calculated each participant's median produced time interval 1, median produced time interval 2, and median produced time ratio (interval 2 divided by interval 1), across trials 14 through 23 and across trials 24 through 42.

## Results

The median produced time intervals 1 and 2, across trials 14 through 23 (Phase 1) and across trials 24 through 42 (Phase 2), and the target interval pairs are shown in Tables 2 and 3 for Phase 1 and Phase 2 respectively.

Table 2

*Experiment 2 -- Group Means (SD) of Median Produced Time Intervals for Trials 14 to 23 (Phase 1)*

| Target Interval Pair (ms) | Produced Intervals (ms) | |
|---|---|---|
| Interval 1:Interval 2 | Interval 1 | Interval 2 |
| 350:350 | 389 (93) | 355 (32) |
| 500:500 | 497 (48) | 469 (56) |
| 700:700 | 697 (39) | 632 (89) |
| 350:700 | 385 (76) | 585 (141) |
| 700:350 | 687 (79) | 375 (83) |
| 500:700 | 557 (53) | 571 (105) |
| 700:500 | 680 (72) | 498 (72) |
| 350:500 | 392 (80) | 458 (64) |
| 500:350 | 522 (65) | 368 (53) |

Table 3

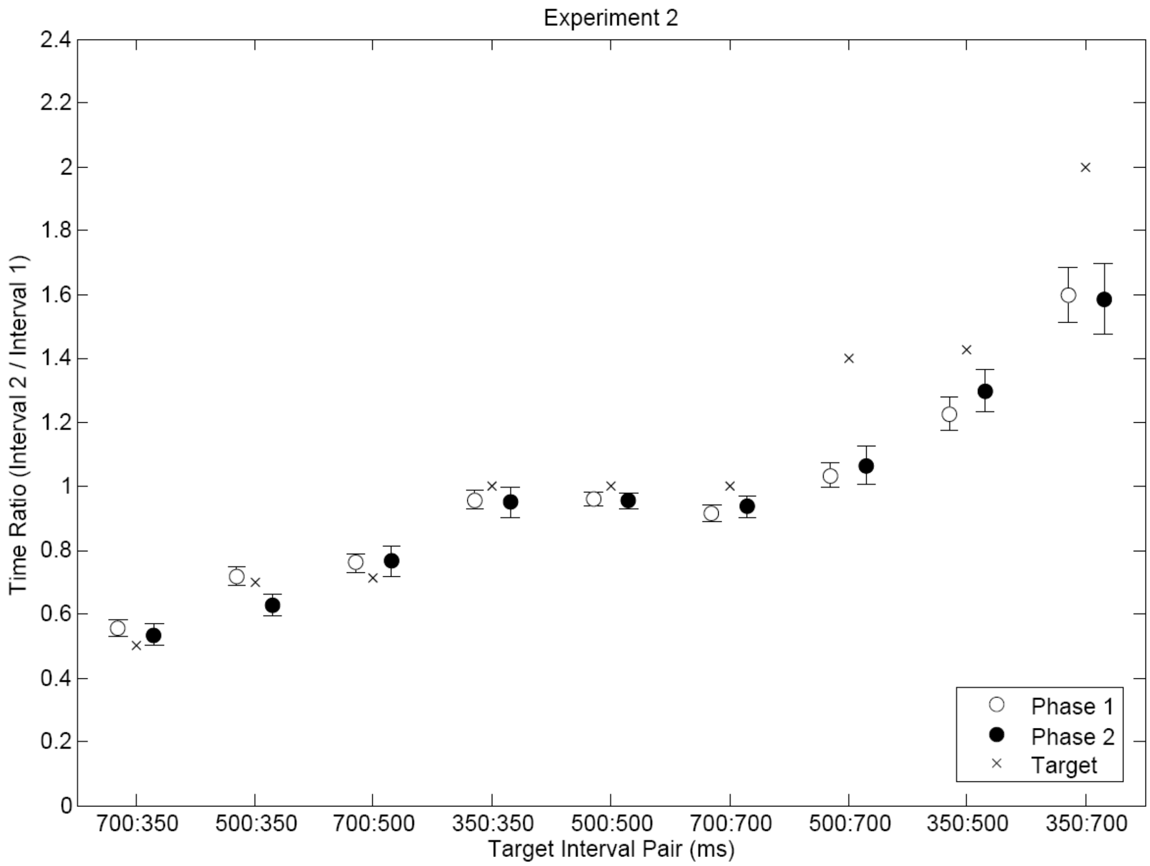
*Experiment 2 -- Group Means (SD) of Median Produced Time Intervals for Trials 24 to 42 (Phase 2)*

| Target Interval Pair (ms) | Produced Intervals (ms) | |
|---|---|---|
| Interval 1:Interval 2 | Interval 1 | Interval 2 |
| 350:350 | 422 (133) | 376 (67) |
| 500:500 | 519 (108) | 483 (56) |
| 700:700 | 707 (82) | 653 (112) |
| 350:700 | 431 (161) | 622 (177) |
| 700:350 | 760 (124) | 393 (101) |
| 500:700 | 606 (138) | 617 (157) |
| 700:500 | 736 (142) | 539 (134) |
| 350:500 | 396 (82) | 503 (107) |
| 500:350 | 625 (164) | 369 (72) |

In the following, I report the analyses I did concerning the median produced time ratios, across trials 14 through 23 (Phase 1) and across trials 24 through 42 (Phase 2), with phase and target interval pair as the within-participants factors. The main effect of phase was not statistically significant, $F(1, 29) = .003$, $p > .10$. The average median produced time ratios for Phase 1 and Phase 2 respectively were .9691 and .9681. To put these two ratio values in context, I note that the average of the ratios formed by the nine target interval pairs is 1.08. I found a statistically significant effect of target interval pair, $F(8, 232) = 53.3$, $p < .01$. In addition, the interaction between phase and target interval pair was not significant, $F(8, 232) = 1.25$, $p > .10$. As can be seen in Figure 5, participants produced similar median time ratios for Phase 1 and Phase 2.

Figure 6 shows the probability of accurately producing the time intervals and time ratios, averaged over participants for each of the three groups of interval pairs. Produced time intervals were considered accurate or correct if both time intervals in a pair fell within ±8.39% of their respective target intervals. A produced time ratio was considered accurate or correct if it fell within −15.48% to +18.32% of the ratio formed by the relevant target interval pair. The average points were fitted by power functions.[4] For most interval-pair groups, the power functions did not fit the data as well as they did in Experiment 1. This is because during Phase 2 of Experiment 2 (i.e., trials 24 to 44) the probability of successful performance tended to either stabilize or decline across trials.

[4] In trial 1, the average probabilities of accurately producing the time interval pairs of the 1:2 and 2:1 interval-pair group and the complex interval-pair group were zero. The power functions were not fit to these data points for the 1:2 and 2:1 group and for the complex group.




| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Ratio: | .56 **.50** .53 | .72 **.70** .63 | .76 **.71** .77 | .96 **1.00** .95 | .96 **1.00** .95 | .91 **1.00** .94 | 1.03 **1.40** 1.06 | 1.23 **1.43** 1.30 | 1.60 **2.00** 1.59 |

**Figure 5.** Median produced time ratios, across trials 14 through 23 (Phase 1) and across trials 24 through 42 (Phase 2), and the time ratios formed by the target interval pairs of Experiment 2. Black crosses represent the time ratios formed by the target interval pairs. White dots and black dots represent the means of the median produced time ratios for Phase 1 and Phase 2 respectively. Vertical bars denote ±1 standard error of the mean. In addition, the time ratios formed by the target interval pairs and the mean produced time ratios for Phase 1 and Phase 2 are displayed below the corresponding target interval pair on the x-axis of the graph. The time ratios formed by the target interval pairs are indicated in bold typeface and situated to the left and right respectively are the mean produced time ratios for Phase 1 and Phase 2.

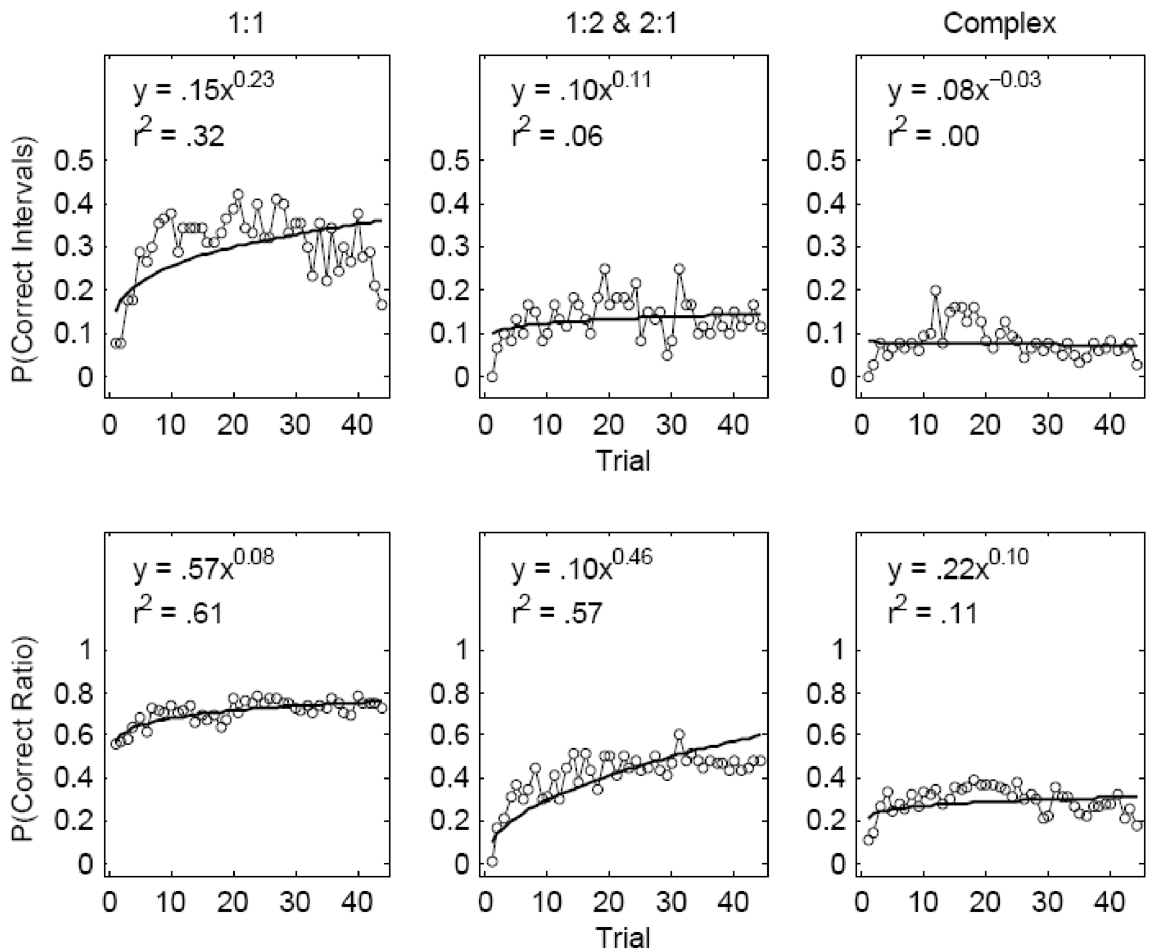



**Figure 6.** Probability of producing the target interval pairs (**top**) and probability of producing the ratios formed by the target interval pairs (**bottom**) averaged over participants for the three groups of interval pairs of Experiment 2. Power functions are fitted to all trials (i.e., trials 1 to 44).

In the analyses of time interval performance and time ratio performance that follow, I treated the three groups of interval pairs (i.e., 1:1 pairs, 1:2 and 2:1 pairs, and complex pairs) as three experimental conditions. This simplification was justified for time interval performance by confirming, via Tukey's Honestly Significant Difference method, that there were significant differences between the three groups in Phase 1 and in Phase 2 but not within any of the groups, with all *p* values exceeding .10 for the latter tests. Similarly, a second Tukey's Honestly Significant Difference Test applied to time ratio performance showed significant differences between the three groups of interval pairs in Phase 1 and in Phase 2. However, in Phase 1, a significant difference was found within the 1:1 group. More specifically, in Phase 1, the probability of producing the ratio formed by the target interval pair was marginally less in the 350-350 ms condition than in the 500-500 ms condition, $p = .08$, and significantly less in the 350-350 ms condition than in the 700-700 ms condition, $p < .01$. In order to justify treating the three 1:1 target interval pairs as a single group, I ran the analyses to be described next with (a) all three 1:1 interval pairs (i.e., 350-350 ms, 500-500 ms, and 700-700 ms) included in the 1:1 group, (b) only the 500-500 ms and 700-700 ms interval pairs included in the 1:1 group, and (c) only the 350-350 ms interval pair included in the 1:1 group. I found no differences between the basic results and statistical conclusions reached from the three analyses. Therefore, in the following, I report only the analysis that included all three 1:1 interval pairs in the 1:1 group.

I analyzed the probabilities of producing the target interval pairs, averaged across trials 14 through 23 (Phase 1) and averaged across trials 24 through 42 (Phase 2), with phase and interval-pair group as the within-participants factors, and, in a second ANOVA, the probabilities of producing the ratios formed by the target interval pairs, with the same design. In the following, I report the analysis of time intervals first, followed by time ratios.

*Time Intervals*

I found a statistically significant main effect of phase, $F(1, 29) = 10.59$, $p < .01$, characterized by a lower probability of success in Phase 2 than in Phase 1. I also found a statistically significant effect of interval-pair group, $F(2, 58) = 46.15$, $p < .01$. The results of a Tukey's HSD Test indicated that: (a) the probability of success in the 1:2 and 2:1 conditions was significantly less than in the 1:1 conditions, $p < .01$; (b) the probability of success in the complex conditions (i.e., 5:7, 7:5, 7:10, and 10:7) was significantly less than in the 1:1 conditions, $p < .01$; and (c) the probability of success in the complex conditions was marginally less than in the 1:2 and 2:1 conditions, $p = .08$. However, the interaction between phase and interval-pair group was not significant, $F(2, 58) = .56$, $p > .10$. Time interval performance for the three interval-pair groups is depicted in the left panel of Figure 7 for Phases 1 and 2 separately.

As for Experiment 1, one concern about these results was that the findings may have reflected unequal numbers of trials in the three groupings. To check this, I re-ran the ANOVA (and accompanying Tukey's HSD Tests) using the first two blocks of trials of the 1:1, 1:2 and 2:1, and complex-ratios conditions. This analysis led to the same basic conclusions as those reached above.

In summary, the results indicated that participants produced time intervals more accurately in Phase 1 than in Phase 2. The results also indicated that participants produced time intervals more accurately in the 1:1 conditions than in the 1:2, 2:1, and complex conditions. There was also some indication that participants produced time intervals in the 1:2 and 2:1 conditions more accurately than in the complex conditions.

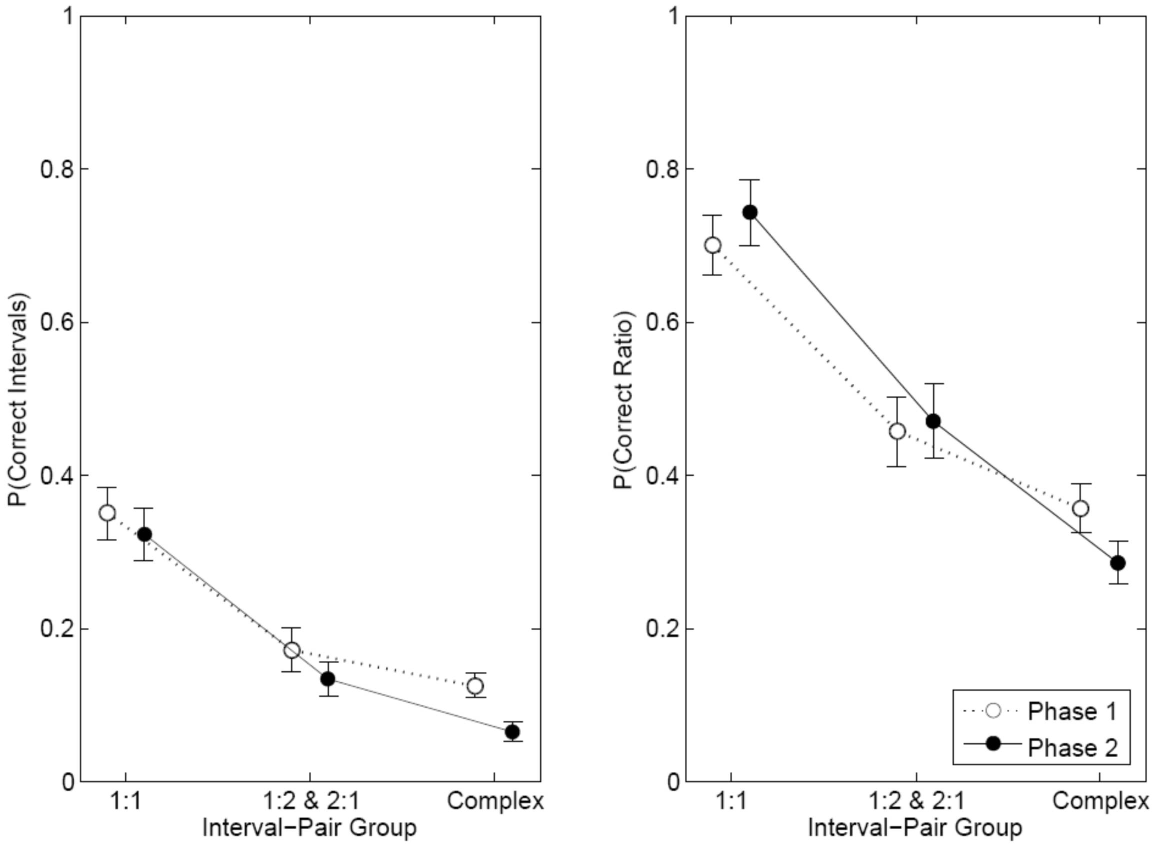



**Figure 7.** Probability of producing the target interval pairs (**left**), averaged across trials 14 through 23 (Phase 1) and averaged across trials 24 through 42 (Phase 2), and probability of producing the associated ratios (**right**), averaged across trials 14 through 23 (Phase 1) and averaged across trials 24 through 42 (Phase 2), for the three groups of interval pairs of Experiment 2. White dots and black dots represent mean performances for Phase 1 and Phase 2 respectively. Vertical bars denote ±1 standard error of the mean.

*Time Ratios*

The main effect of phase was not statistically significant, $F(1, 29) = .12$, $p > .10$. I found a statistically significant effect of interval-pair group, $F(2, 58) = 55.9$, $p < .01$. The results of a Tukey's HSD Test indicated that: (a) the probability of success in the 1:2 and 2:1 conditions was significantly less than in the 1:1 conditions, $p < .01$; (b) the probability of success in the complex conditions (i.e., 5:7, 7:5, 7:10, and 10:7) was significantly less than in the 1:1 conditions, $p < .01$; and (c) the probability of success in the complex conditions was significantly less than in the 1:2 and 2:1 conditions, $p < .01$. In addition, the interaction between phase and interval-pair group was significant, $F(2, 58) = 4.9$, $p = .01$.

As can be seen in the right panel of Figure 7, the interaction can be characterized as slightly higher performance levels in Phase 2 than in Phase 1 for the 1:1 conditions and the 1:2 and 2:1 conditions and lower performance levels in Phase 2 than in Phase 1 for the complex conditions. Regarding these comparisons, a Tukey's HSD Test showed that the difference between Phase 1 and Phase 2 performance approached statistical significance only for the complex conditions, $p = .0999$.

Once again, I addressed the issue of unequal numbers of trials for the three groupings by repeating the analysis but for the first two blocks of trials only of each grouping. This analysis led to the same basic conclusions as those reached above. The only exception was that the interaction between phase and interval-pair group was not statistically significant, whereas in the original analysis this interaction was statistically significant. Still, the two analyses led to qualitatively similar results in terms of the relation between ratio performance and interval-pair group in Phase 1 and in Phase 2.

In summary, the results indicated that participants produced time ratios more accurately in the 1:1 conditions than in the 1:2, 2:1, and complex conditions. Participants also produced time ratios in the 1:2 and 2:1 conditions more accurately than in the complex conditions. In addition, participants did not produce time ratios more accurately in Phase 1 than in Phase 2 in the 1:1, 1:2, and 2:1 conditions. However, there was some indication that participants produced time ratios more accurately in Phase 1 than in Phase 2 in the complex conditions.

## Discussion

The results of Experiment 2 showed that when KR was available (Phase 1) and also when KR was removed (Phase 2), participants produced intervals and ratios best in the 1:1 conditions, worst in the complex conditions, and in-between in the 1:2 and 2:1 conditions (although, the difference between the complex conditions and the 1:2 and 2:1 conditions was only marginally significant for time interval performance).

The 1:2 and 2:1 advantages (relative to performance in the complex conditions) observed in Phase 2 are consistent with the hypothesis that the source of these advantages in unimanual tapping is internal representations based on real-time sensory information. The removal of KR in Phase 2 may have resulted in participants focusing on the perceptual consequences of their finger tapping (e.g., auditory or kinesthetic feedback) which can be taken to suggest that the source of the 1:2 and 2:1 advantages may have been real-time perceptual information that participants derived from their own actions.

However, the 1:2 and 2:1 advantages observed in Phase 1 of Experiment 2 (KR available) do not conform to my prediction that these advantages should be eliminated when KR is available. This result could be seen as a failure to replicate Experiment 1 where I found that participants produced intervals and ratios equally well in the complex, 1:2, and 2:1 conditions when KR was available (as it always was in the first experiment). However, two differences between the methods of Experiments 1 and 2 may explain why the Phase 1 results of Experiment 2 did not match the results of Experiment 1. The first was that Experiment 1 had 42 trials with KR whereas Experiment 2 had only 22 trials with KR. The second was that Experiment 1 did not have a continuation phase whereas Experiment 2 did. Conceivably, participants' difficulties in producing complex interval-pairs and ratios in Phase 1 of Experiment 2 may have reflected an increased focus on the real-time perceptual consequences of their actions in anticipation of the upcoming continuation phase (Phase 2).

To assess which of these two differences was more important, I turned to a subset of data from 13 participants in Experiment 1. This subset included a 1:2 or 2:1 interval-pair condition and a complex interval-pair condition (i.e., 5:7, 7:5, 7:10, or 10:7) for each participant. I selected the data subset I did so the amount of exposure to the task prior to performing in the 1:2 and 2:1 conditions and the complex conditions was matched across participants. I took this precaution to rule out unequal amounts of practice as an explanation of any potential differences in performance between the two groups of interval pairs in the analyses that follow (i.e., 1:2 and 2:1 versus complex). An additional constraint that I placed on this data set was that participants experienced the 1:2 or 2:1 condition and the complex condition during blocks 1, 2, 3, or 4 (I excluded blocks 5 through 9 from the analysis). I restricted the data set in this way in order to rule out unequal amounts of exposure to trials with KR as an explanation of any potential differences between the results of the current analysis and the corresponding results from Phase 1 of Experiment 2.

For the two groups of interval pairs, I calculated each participant's probability of success, averaged across trials 14 through 23, for producing the target interval pairs and for producing the associated ratios. These were the same trials that were analyzed in Phase 1 of Experiment 2. I reasoned that if participants in Phase 1 of Experiment 2 performed less accurately in the complex conditions than in the 1:2 and 2:1 conditions because they were exposed to too few trials with KR, then participants in the subset of Experiment 1 would have also performed less accurately in the complex conditions than in the 1:2 and 2:1 conditions. By contrast, if participants in Phase 1 of Experiment 2 performed less accurately in the complex conditions than in the 1:2 and 2:1 conditions because of their expectation of going on without KR in the continuation phase, then participants in the subset of Experiment 1 who were not exposed to a continuation phase would perform equally well in the complex, 1:2, and 2:1 conditions.

Produced time intervals were considered accurate or correct if both time intervals in a pair fell within ±8.39% of their respective target intervals. I defined the time ratio as interval 2 divided by interval 1. A produced time ratio was considered accurate or correct if it fell within −15.48% to +18.32% of the ratio formed by the relevant target interval pair.

To test these predictions, I conducted two matched-samples *t*-tests. The first compared the probabilities of producing the target <u>interval</u> pairs, averaged across trials 14 through 23, in the 1:2 and 2:1 conditions and the complex conditions. The second compared the probabilities of producing the <u>ratios</u> formed by the target interval pairs, averaged across trials 14 through 23, in the 1:2 and 2:1 conditions and the complex conditions. Both *t*-tests failed to reach significance: $t(12) = -1.6$, $p > .10$, for time intervals, and $t(12) = -.46$, $p > .10$, for time ratios. This outcome indicates that participants in the subset of Experiment 1 performed equally well in the complex, 1:2, and 2:1 conditions, indicating that participants did not simply have too few trials with KR in Phase 1 of Experiment 2 to perform equally well in the complex, 1:2, and 2:1 conditions. By implication, the hypothesis that is better supported, or less resoundingly rejected, is that participants' difficulties in the complex conditions in Phase 1 of Experiment 2 stemmed from their anticipated continuation of the task without KR in the second phase of that experiment.

Finally, I note that the 1:2 and 2:1 advantages (relative to performance in the complex conditions) observed in the discrete-trial shaping and continuation procedures used in Experiment 2 are not consistent with the hypothesis that I previously raised. This hypothesis stated that the discrete-trial aspect of the shaping procedure used in Experiment 1 may have played a role in eliminating the 1:2 and 2:1 advantages in that task.

# Chapter 4. EXPERIMENT 3

Experiment 3 was designed to provide a more rigorous test of the hypothesis that the source of the 1:2 and 2:1 interval-ratio advantages in unimanual tapping is internal representations based on real-time sensory information. I addressed this challenge by having participants perform a discrete-trial imitation task and also a discrete-trial shaping task similar to the one described in Experiment 1 (i.e., KR provided to participants after all trials). I note that participants were not provided with KR in the imitation task. The hypothesis would be supported if the 1:2 and 2:1 advantages were observed in the imitation task and eliminated in the shaping task. These predictions are based on the idea that participants process real-time sensory information in imitation tasks because KR is unavailable and that participants do not process real-time sensory information in shaping tasks because KR is available.

## Method

### *Participants*

Twenty healthy people (15 female and 5 male) participated in this experiment. Sixteen participants were Penn State students who participated for course credit or were recruited by placing flyers around the campus and paid $9. The remaining four participants were recruited via flyers and paid $9; their education levels ranged from no college degree to a master's degree, but none were students at the time of their participation. Nineteen participants were right-handed and one was left-handed. Participants reported musical training that ranged from no training whatsoever to eight years training on a musical instrument including voice [this information was obtained via question 3 of the Ollen Musical Sophistication Index Questionnaire (Ollen, 2006)]. All participants were naive to the hypotheses, and none had been in any of the previous experiments. I excluded two additional participants (independent of the twenty participants just described) from the data analyses that follow because they reported partial hearing loss.

*Apparatus*

The apparatus was the same as in Experiment 1 with the addition of two Dell A225 speakers that produced clicking sounds for the imitation task. The sounds were generated in Matlab with a Wave Sound file.

*Procedure and Design*

Each participant performed a shaping task and an imitation task. Half the participants performed the shaping task first followed by the imitation task and the other half of the participants performed the two tasks in the reverse order.

The procedure for the shaping task was identical to Experiment 1. The only difference was that I tested only a subset of the time interval pairs from Experiment 1. The interval pairs in milliseconds (and their ratios) that I tested are as follows:

| | |
|---|---|
| 350-350 | (1:1) |
| 350-500 | (7:10) |
| 350-700 | (1:2) |
| 500-350 | (10:7) |
| 700-350 | (2:1) |

This smaller set of interval pairs includes the same basic interval ratios that I tested in the larger set of Experiment 1. I accomplished this by retaining only one instance (i.e., one interval pair) of each interval ratio from Experiment 1. Because of the addition of the imitation task -- to be described next -- this reduction in the number of interval pairs was necessary to keep the duration of the experimental sessions at approximately one hour (as was the case for Experiment

1) thereby eliminating the potential for increased fatigue and boredom that may accompany longer sessions.

In the imitation task I asked participants to press the spacebar with the index finger of their dominant hand in a way that mimicked the timing of a series of three clicking sounds (clicks) generated by the computer. The participants were instructed that for each trial, they should first listen to all three clicks and then, when ready, imitate the timing of the clicks by pressing the spacebar three times. Each spacebar press caused the computer to generate the same clicking sound.

As was the case for the shaping task of this experiment, participants in the imitation task performed five blocks of 42 trials each. Each block tested one of the five interval pairs that were also tested in the shaping task (the five interval pairs are presented above). That is, the time intervals that participants were asked to imitate were the same time intervals that participants were asked to learn through trial-and-error in the shaping task.

For the shaping and imitation tasks, each participant completed five blocks of trials, with each block testing a unique pair of target time intervals. Each participant was randomly assigned three of the five interval pairs for practice. Five trials were completed for each of the three practice blocks. In the experiment, the full set of five interval pairs were presented to each participant in a different random order for each participant.

*Data Analysis*

For the shaping and imitation tasks, I calculated the probability of producing the target interval pairs and the ratios formed by the target interval pairs using the same accuracy criteria as in Experiment 1. I analyzed time intervals by assessing the probability that both intervals produced in the trials of a block fell within ±8.39% of their respective target intervals. This percentage ensured that the allowable ranges for different target intervals did not overlap.

I analyzed the time ratios by calculating the probability that the ratios, defined as interval 2 divided by interval 1, produced in the trials of a block fell within −15.48% to +18.32% of the ratio formed by the relevant target interval pair. These percentages were derived from the upper and lower limits of the allowable ranges associated with the target interval pairs. Critically, the allowable ranges for the ratios formed by the different target interval pairs did not overlap.

For purposes of data analysis, I placed the five target interval pairs into three groups: (a) the 1:1 pair (350-350 ms); (b) the 1:2 and 2:1 pairs (350-700 ms and 700-350 ms); and (c) the 7:10 and 10:7 pairs (350-500 ms and 500-350 ms).

For the shaping and imitation tasks separately, for each group of interval pairs, I calculated each participant's probability of success, averaged across trials 24 through 42, for producing the target interval pairs and for producing the associated ratios. I chose to analyze average performance for the last 19 trials in each block of trials (i.e., trials 24 to 42) because I thought the effects of shaping would be most apparent in these later trials. I analyzed the same set of trials for the imitation task in order to facilitate comparing performance between the imitation and shaping tasks.

In addition, for the shaping and imitation tasks separately, for each target interval pair, I calculated each participant's median produced time interval 1, median produced time interval 2, and median produced time ratio (interval 2 divided by interval 1), across trials 24 through 42.

## Results

The median produced time intervals 1 and 2, across trials 24 through 42, and the target interval pairs are shown in Tables 4 and 5 for the shaping task and imitation task respectively.

Table 4

*Experiment 3 Shaping Task -- Group Means (SD) of Median Produced Time Intervals for Trials 24 to 42*

| Target Interval Pair (ms) | Produced Intervals (ms) | |
|---|---|---|
| Interval 1:Interval 2 | Interval 1 | Interval 2 |
| 350:350 | 364 (25) | 360 (42) |
| 350:700 | 387 (44) | 577 (110) |
| 700:350 | 681 (84) | 381 (85) |
| 350:500 | 369 (41) | 482 (57) |
| 500:350 | 508 (52) | 360 (46) |

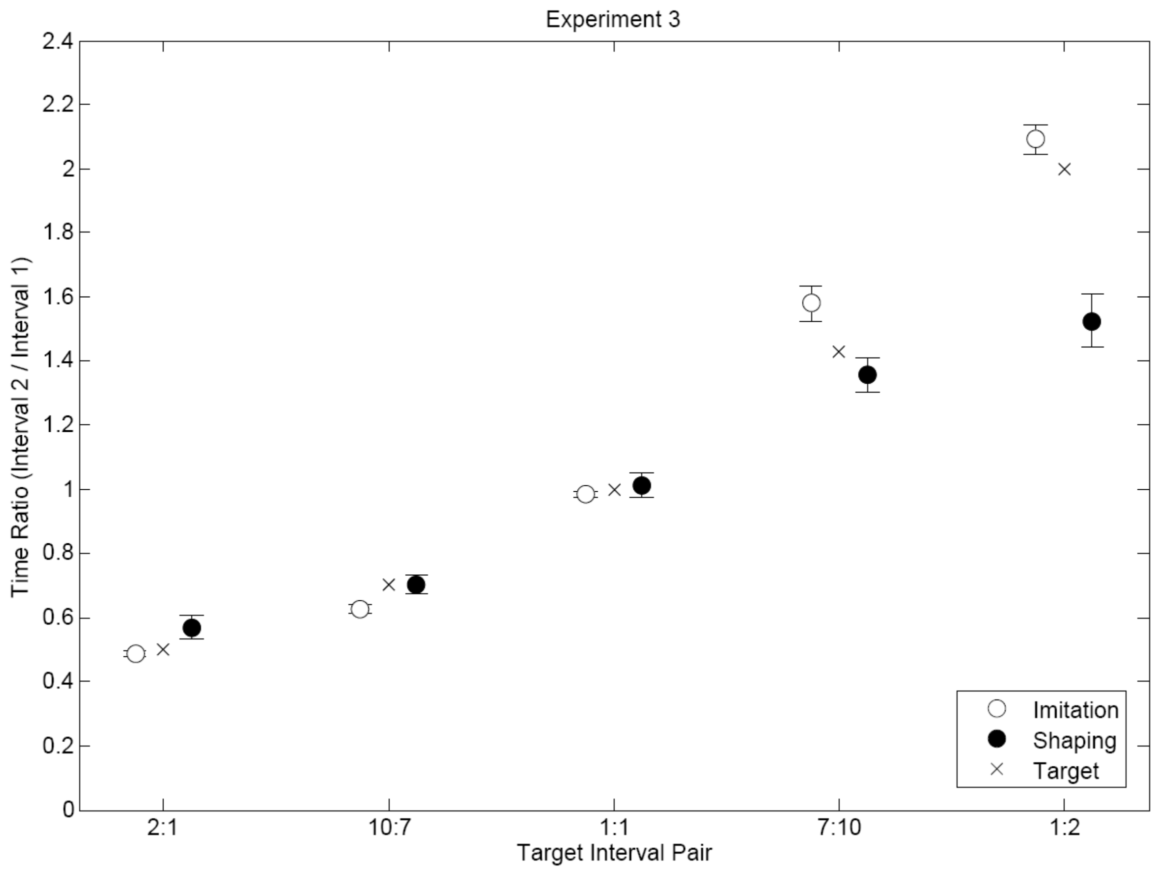
Table 5

*Experiment 3 Imitation Task -- Group Means (SD) of Median Produced Time Intervals for Trials 24 to 42*

| Target Interval Pair (ms) | Produced Intervals (ms) | |
|---|---|---|
| Interval 1:Interval 2 | Interval 1 | Interval 2 |
| 350:350 | 347 (15) | 341 (15) |
| 350:700 | 340 (14) | 710 (58) |
| 700:350 | 704 (47) | 341 (17) |
| 350:500 | 342 (36) | 533 (61) |
| 500:350 | 537 (65) | 334 (24) |

In the following, I report the analyses I did concerning the median produced time ratios, across trials 24 through 42, with task (shaping versus imitation) and target interval pair as the within-participants factors. I found a statistically significant main effect of task, $F(1, 19) = 18.30$, $p < .01$, characterized by average median produced time ratios of 1.03 for the shaping task and 1.15 for the imitation task. To put these two ratio values in context, I note that the average of the ratios formed by the five target interval pairs is 1.13. I also found a statistically significant effect of target interval pair, $F(4, 76) = 267.99$, $p < .01$. The time ratios formed by the target interval pairs and the median produced time ratios, averaged over the shaping and imitation tasks, for the 1:1, 1:2, 2:1, 7:10, and 10:7 conditions, were as follows: (a) 1, .9986; (b) 2, 1.8077; (c) .50, .5273; (d) 1.4286, 1.4685; and (e) .70, .6644. In addition, the interaction between task and target interval pair was significant, $F(4, 76) = 26.50$, $p < .01$.

As can be seen in Figure 8, for the shaping task, the mismatches between the produced time ratios and the time ratios formed by the target interval pairs generally increased as the latter ratios deviated from 1:1. Furthermore, the produced time ratios veered in the direction of 1:1. On the other hand, for the imitation task, the mismatches between the produced time ratios and the time ratios formed by the target interval pairs were the largest for the 7:10 and 10:7 conditions. Furthermore, the produced time ratios veered in the direction of 1:2 and 2:1 for the 7:10 and 10:7 target interval pairs, respectively.




| Ratio: | 2:1 | 10:7 | 1:1 | 7:10 | 1:2 |
|---|---|---|---|---|---|
| | .49 **.50** .57 | .63 **.70** .70 | .98 **1.00** 1.01 | 1.58 **1.43** 1.36 | 2.09 **2.00** 1.52 |

**Figure 8.** Median produced time ratios, across trials 24 through 42, and the time ratios formed by the target interval pairs for the shaping and imitation tasks of Experiment 3. Black crosses represent the time ratios formed by the target interval pairs. White dots and black dots represent the means of the median produced time ratios for the imitation task and the shaping task respectively. Vertical bars denote ±1 standard error of the mean. In addition, the time ratios formed by the target interval pairs and the mean produced time ratios for the imitation task and the shaping task are displayed below the corresponding target interval pair on the x-axis of the graph. The time ratios formed by the target interval pairs are indicated in bold typeface and situated to the left and right respectively are the mean produced time ratios for the imitation and shaping tasks.

Figures 9 and 10 show the probability of accurately producing the time intervals and of accurately producing the time ratios, averaged over participants for each of the three groups of interval pairs, for the shaping and imitation tasks respectively. Produced time intervals were considered accurate or correct if both time intervals in a pair fell within ±8.39% of their respective target intervals. A produced time ratio was considered accurate or correct if it fell within −15.48% to +18.32% of the ratio formed by the relevant target interval pair. For the shaping task, the average points were fitted by power functions that characterized the increase in the probability of successful performance over practice (i.e., as a function of trial) for all groups of interval pairs.[5] On the other hand, for the imitation task, the average points were fitted by power functions that characterized the relatively constant probability of successful performance across trials for all groups of interval pairs.

[5] In trial 1 of the shaping task, the average probability of accurately producing the time interval pairs of the 7:10 and 10:7 interval-pair group was zero. The power function was not fit to this data point for the 7:10 and 10:7 group of the shaping task.

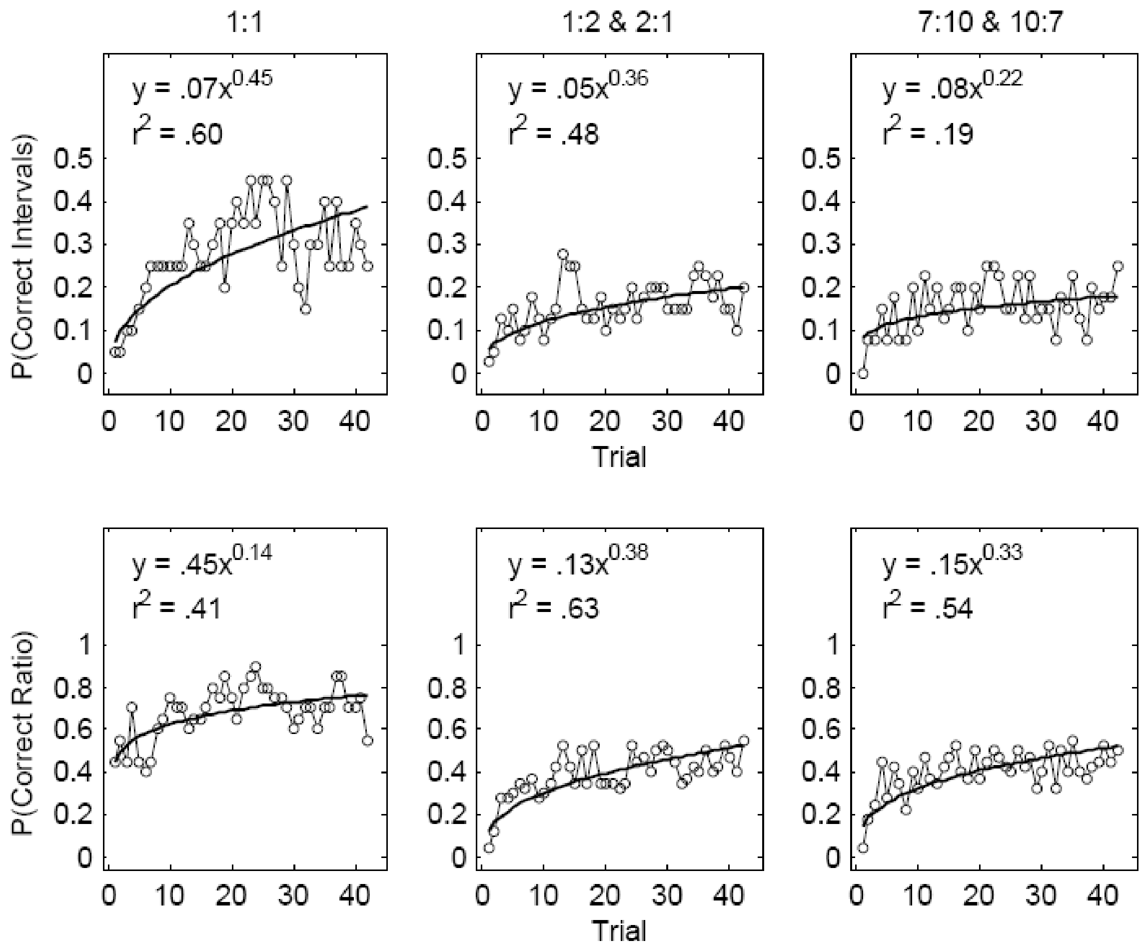



**Figure 9.** Probability of producing the target interval pairs (**top**) and probability of producing the ratios formed by the target interval pairs (**bottom**) averaged over participants for the three groups of interval pairs for the shaping task of Experiment 3. Power functions are fitted to all trials (i.e., trials 1 to 42).

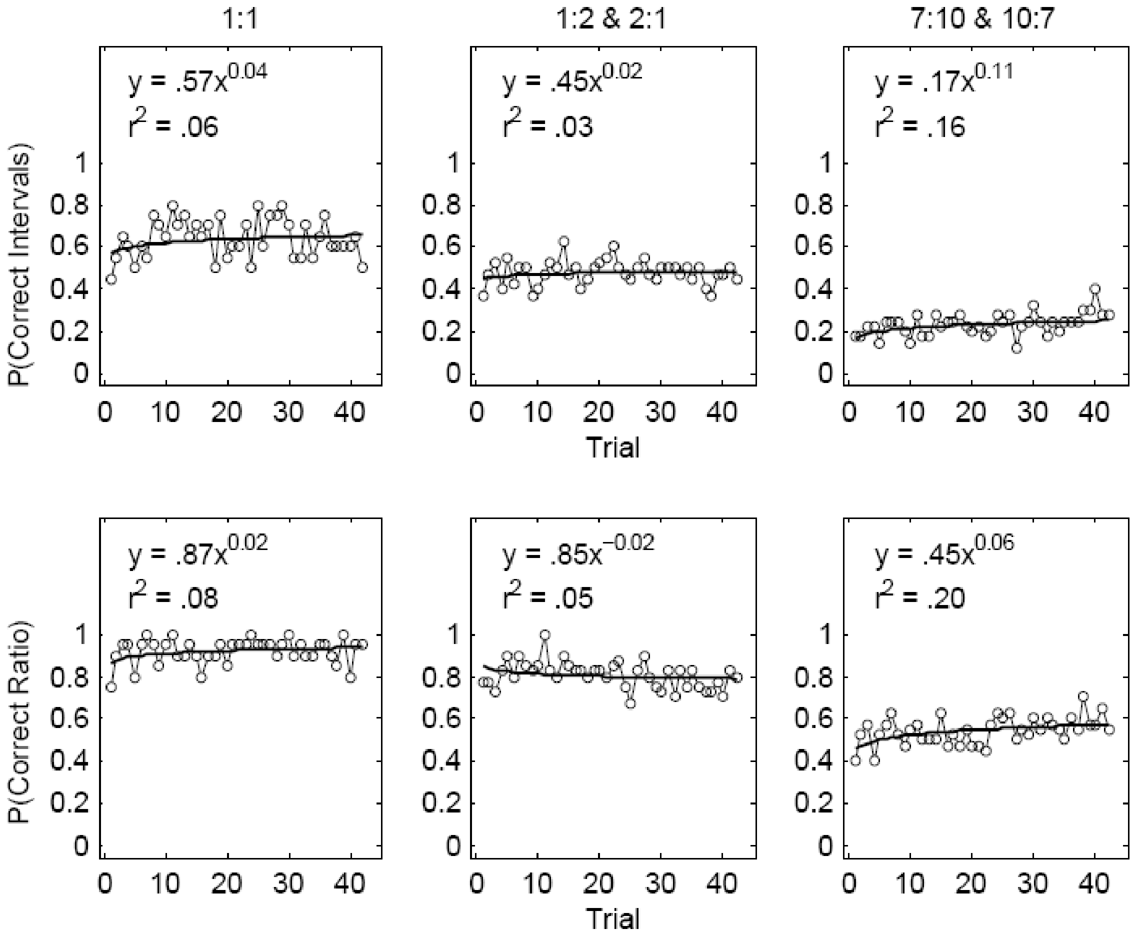



**Figure 10.** Probability of producing the target interval pairs (**top**) and probability of producing the ratios formed by the target interval pairs (**bottom**) averaged over participants for the three groups of interval pairs for the imitation task of Experiment 3. Power functions are fitted to all trials (i.e., trials 1 to 42).

In the analyses of time interval performance and time ratio performance that follow, I treated the three groups of interval pairs (i.e., 1:1 pair, 1:2 and 2:1 pairs, and 7:10 and 10:7 pairs) as three experimental conditions. This simplification was justified by confirming, via Tukey's Honestly Significant Difference method, that there were significant differences between the three groups for the shaping task and for the imitation task but never within either of the latter two groups (i.e., 1:2 and 2:1 pairs and 7:10 and 10:7 pairs), with all $p$ values exceeding .10 for the latter tests. This was confirmed for time interval performance and time ratio performance separately. I analyzed the probabilities of producing the target interval pairs, averaged across trials 24 through 42, with task (shaping versus imitation) and interval-pair group as the within-participants factors, and, in a second ANOVA, the probabilities of producing the ratios formed by the target interval pairs, with the same design. In the following, I report the analysis of time intervals first, followed by time ratios.

*Time Intervals*

I found a statistically significant main effect of task, $F(1, 19) = 72.26$, $p < .01$, characterized by a lower probability of success in the shaping task than in the imitation task. I also found a statistically significant effect of interval-pair group, $F(2, 38) = 26.06$, $p < .01$. The results of a Tukey's HSD Test indicated that: (a) the probability of success in the 1:2 and 2:1 conditions was significantly less than in the 1:1 condition, $p < .01$; (b) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:1 condition, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:2 and 2:1 conditions, $p = .01$. In addition, the interaction between task and interval-pair group was significant, $F(2, 38) = 5.15$, $p = .01$.

As can be seen in Figure 11 (top left graph), the interaction can be characterized as larger differences between the performance levels of the imitation task and the shaping task for the 1:1, 1:2, and 2:1 conditions than the 7:10 and 10:7 conditions. These observations were confirmed via a Tukey's HSD Test. It was shown that: (a) the probability of success in the 1:1 condition was significantly less in the shaping task than in the imitation task, $p < .01$; (b) the probability of success in the 1:2 and 2:1 conditions was significantly less in the shaping task than in the imitation task, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was not significantly less in the shaping task than in the imitation task, $p > .10$.

As is also apparent in Figure 11 (top left graph), a second way of characterizing the interaction is that the shaping task resulted in only two levels of performance across the three interval-pair groups whereas the imitation task resulted in three levels of performance, one for each interval-pair group. More specifically, it appears that for the shaping task, performance levels were higher for the 1:1 condition than the 1:2, 2:1, 7:10, and 10:7 conditions, with no difference between the 1:2 and 2:1 conditions and the 7:10 and 10:7 conditions. On the other hand, for the imitation task, Figure 11 (top left graph) suggests that the probability of success was highest for the 1:1 condition, lowest for the 7:10 and 10:7 conditions, and in-between for the 1:2 and 2:1 conditions. These observations were generally confirmed via a Tukey's HSD Test. For the shaping task, it was shown that: (a) the probability of success in the 1:2 and 2:1 conditions was not significantly less than in the 1:1 condition, although it was close to being marginally significant, $p = .13$; (b) the probability of success in the 7:10 and 10:7 conditions was marginally less than in the 1:1 condition, $p = .07$; and (c) the probability of success in the 7:10 and 10:7 conditions was not significantly less than in the 1:2 and 2:1 conditions, $p = 1$. For the imitation task, it was shown that: (a) the probability of success in the 1:2 and 2:1 conditions was significantly less than in the 1:1 condition, $p < .05$; (b) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:1 condition, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:2 and 2:1 conditions, $p < .01$.

To summarize, the results indicated that participants produced time intervals more accurately in the imitation task than in the shaping task in the 1:1, 1:2, and 2:1 conditions but not in the 7:10 and 10:7 conditions. With regard to the shaping task, there was some indication that participants produced time intervals more accurately in the 1:1 condition than in the 1:2, 2:1, 7:10, and 10:7 conditions (although this did not reach statistical significance), but participants did not produce time intervals more accurately in the 1:2 and 2:1 conditions than in the 7:10 and 10:7 conditions. Finally, in the imitation task, participants produced time intervals more accurately in the 1:1 condition than in the 1:2, 2:1, 7:10, and 10:7 conditions. Participants also produced time intervals in the 1:2 and 2:1 conditions more accurately than in the 7:10 and 10:7 conditions.

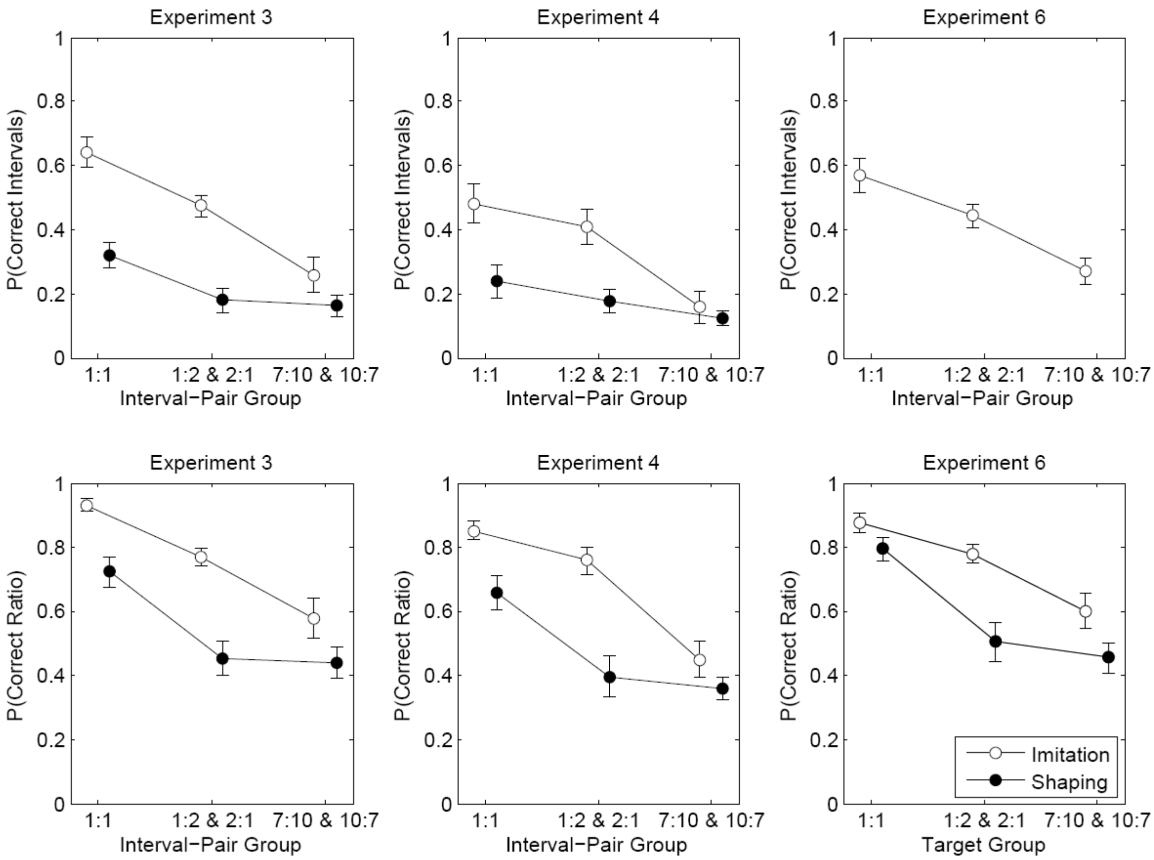



**Figure 11.** Probability of producing the target interval pairs (**top**), averaged across trials 24 through 42, and probability of producing the associated ratios (**bottom**), averaged across trials 24 through 42, for the three groups of interval pairs or target groups for Experiments 3, 4, and 6. Results for Experiments 3, 4, and 6 are displayed at the left, center, and right, respectively. White dots and black dots represent mean performances for the imitation tasks and the shaping tasks respectively. Vertical bars denote ±1 standard error of the mean.

*Time Ratios*

I found a statistically significant main effect of task, $F(1, 19) = 46.02$, $p < .01$, characterized by a lower probability of success in the shaping task than in the imitation task. I also found a statistically significant effect of interval-pair group, $F(2, 38) = 26.19$, $p < .01$. The results of a Tukey's HSD Test indicated that: (a) the probability of success in the 1:2 and 2:1 conditions was significantly less than in the 1:1 condition, $p < .01$; (b) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:1 condition, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was marginally less than in the 1:2 and 2:1 conditions, $p = .07$. In addition, the interaction between task and interval-pair group was marginally significant, $F(2, 38) = 2.76$, $p = .08$.

As can be seen in Figure 11 (bottom left graph), the interaction can be characterized as larger differences between the performance levels of the imitation task and the shaping task for the 1:1, 1:2, and 2:1 conditions than the 7:10 and 10:7 conditions. These observations were confirmed via a Tukey's HSD Test. It was shown that: (a) the probability of success in the 1:1 condition was significantly less in the shaping task than in the imitation task, $p < .01$; (b) the probability of success in the 1:2 and 2:1 conditions was significantly less in the shaping task than in the imitation task, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was not significantly less in the shaping task than in the imitation task, $p = .13$.

As is also apparent in Figure 11 (bottom left graph), a second way of characterizing the interaction is that the shaping task resulted in only two levels of performance across the three interval-pair groups whereas the imitation task resulted in three levels of performance, one for each interval-pair group. More specifically, it appears that for the shaping task, performance levels were higher for the 1:1 condition than the 1:2, 2:1, 7:10, and 10:7 conditions, with no difference between the 1:2 and 2:1 conditions and the 7:10 and 10:7 conditions. On the other hand, for the imitation task, Figure 11 (bottom left graph) suggests that the probability of success was highest for the 1:1 condition, lowest for the 7:10 and 10:7 conditions, and in-between for the 1:2 and 2:1 conditions. These observations were generally confirmed via a Tukey's HSD Test. For the shaping task, it was shown that: (a) the probability of success in the 1:2 and 2:1 conditions was significantly less than in the 1:1 condition, $p < .01$; (b) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:1 condition, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was not significantly less than in the 1:2 and 2:1 conditions, $p > .10$. For the imitation task, it was shown that: (a) the probability of success in the 1:2 and 2:1 conditions was marginally less than in the 1:1 condition, $p = .053$; (b) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:1 condition, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:2 and 2:1 conditions, $p = .01$.

To summarize, the results indicated that participants produced time ratios more accurately in the imitation task than in the shaping task in the 1:1, 1:2, and 2:1 conditions but not in the 7:10 and 10:7 conditions. With regard to the shaping task, participants produced time ratios more accurately in the 1:1 condition than in the 1:2, 2:1, 7:10, and 10:7 conditions, but participants did not produce time ratios more accurately in the 1:2 and 2:1 conditions than in the 7:10 and 10:7 conditions. Finally, in the imitation task: (a) there was some indication that participants produced time ratios more accurately in the 1:1 condition than in the 1:2 and 2:1 conditions, although this result just missed reaching statistical significance; (b) participants produced time ratios more accurately in the 1:1 condition than in the 7:10 and 10:7 conditions;

and (c) participants produced time ratios in the 1:2 and 2:1 conditions more accurately than in the 7:10 and 10:7 conditions.

## Discussion

The results of the shaping task used in Experiment 3 replicated the basic findings of the shaping task used in Experiment 1. The shaping results indicated that 1:1 time ratios were easier to perform than the other ratios that I tested. However, I obtained no evidence that 1:2 and 2:1 time ratios were easier to perform than the 7:10 and 10:7 ratios. On the other hand, the results of the imitation task used in Experiment 3 indicated that 1:1, 1:2, and 2:1 time ratios were easier to perform than the 7:10 and 10:7 ratios. These results are consistent with the hypothesis that the source of the 1:2 and 2:1 time-ratio advantages in unimanual tapping is internal representations based on real-time sensory information. This interpretation is based on the idea that participants processed real-time sensory information in the imitation task (e.g., the sequence of clicks generated by the computer and their finger taps) because KR was unavailable and that participants did not process real-time sensory information in the shaping task because KR was available. It is also plausible that real-time perceptual information was the source of the 1:1 advantage in the imitation task. However, because a 1:1 advantage was also observed in the shaping task, this advantage may have more than one contributing factor. For instance, the 1:1 advantage may also derive from cognitive efficiencies associated with replicating a single interval rather than producing two different time intervals, as required for all other time ratios.

An alternative interpretation of the results is that the 1:2 and 2:1 interval-ratio advantages were eliminated in the shaping task because the KR allowed participants to independently represent the time intervals. If the time intervals were represented independently, there is no reason to suspect that the relation between intervals (i.e., time ratio) should influence performance. On the other hand, in the absence of KR, participants in the imitation task may have represented the relation between the time intervals in addition to the time intervals themselves. As discussed later, Experiments 5 and 6 were designed to address this alternative interpretation of the results of Experiment 3.

In addition to the shaping task providing participants with KR and the imitation task not providing participants with KR, another difference between the two tasks was the proportion of trials that, in effect, called for participants to replicate their timing from previous trials. Presumably, the proportion of such trials was high for the imitation task because the target timing indicated by the metronome was constant within a block of trials. In comparison, a lower proportion of trials in the shaping task would have called for participants to replicate their timing from previous trials because success depended on adjusting one's timing in response to KR. Even when participants were successful, the ensuing reduction in the accuracy bands would have necessitated adjustments on subsequent trials. Based on the idea that the opportunity to replicate may encourage participants to form long-term or stable memories of time intervals, I am proposing that the 1:2 and 2:1 advantages observed in the imitation task may have been linked to long-term memory. I note that Povel (1981) offered a similar account of the 1:2 and 2:1 advantages in a synchronization-continuation task. Accordingly, this alternative account of the Experiment 3 results suggests that the reason the 1:2 and 2:1 advantages were not observed in the shaping task was that participants were discouraged from forming long-term memories by insufficient opportunities to replicate their timing. These predictions could be tested by a future study that implements a version of the imitation task used in Experiment 3 in which the time interval pair to be imitated varies randomly from trial-to-trial within a block. The idea is that random variation of time interval pairs would reduce trial-to-trial replication which may discourage participants from forming long-term memories. Therefore, if the 1:2 and 2:1 advantages depend on replication, then they should be reduced in such a task because trial-to-trial replication is reduced.

Another main finding of the current experiment was that participants achieved higher levels of performance in the imitation task than the shaping task. This finding may be attributed to the shaping task requiring more cognitive operations than the imitation task. For example, although both tasks required time estimation, the shaping task may have placed greater demands on working memory and decision processes. To succeed in the shaping task it is plausible that participants had to maintain an active representation of the time intervals from the trial they just completed while they processed visual feedback (KR) and decided what time intervals to produce on the next trial.

A final note about the results of Experiment 3 is that the 1:2 and 2:1 advantages (relative to performance in the complex conditions) observed in the imitation task are not consistent with the hypothesis that I previously raised. This hypothesis stated that a discrete-trial design may be a key factor in eliminating the 1:2 and 2:1 interval-ratio advantages for unimanual tapping. Evidently, this is not the case.

## Chapter 5. EXPERIMENT 4

Experiment 4 was designed to test whether the findings of Experiment 3 could be replicated with a different set of time interval pairs that comprised the same interval ratios. This provided a test of whether the relations between performance and required time-interval-ratios for the shaping and imitation tasks were independent of other properties of a set of time intervals. For example, the sets of time intervals tested in Experiments 3 and 4 differed in terms of the intervals themselves and in terms of the rules that were used to generate the interval pairs. The differences between the rules that were used to generate the sets of time interval pairs in Experiments 3 and 4 are discussed in more detail below. Therefore, the current experiment was identical to Experiment 3 in all respects except that it tested a different set of time interval pairs.

### Method

*Participants*

Twenty healthy people (11 female and 9 male) participated in this experiment. Fifteen participants were Penn State students who participated for course credit or were recruited by placing flyers around the campus and paid $9. The remaining five participants were recruited via flyers and paid $9; their education levels ranged from no college degree to a doctoral degree, but none were students at the time of their participation. Nineteen participants were right-handed and one was left-handed. Participants reported musical training that ranged from no training whatsoever to ten years training on a musical instrument including voice [this information was obtained via question 3 of the Ollen Musical Sophistication Index Questionnaire (Ollen, 2006)]. All participants were naive to the hypotheses, and none had been in any of the previous experiments. I excluded an additional participant (independent of the twenty participants just described) from the data analyses that follow because of persistent noise that occurred during the experimental session due to construction in an adjacent room.

*Apparatus*

The apparatus was the same as in Experiment 3.

*Procedure and Design*

As in Experiment 3, each participant performed a shaping task and an imitation task. Half the participants performed the shaping task first followed by the imitation task and the other half of the participants performed the two tasks in the reverse order.

The procedures for the shaping task and the imitation task were identical to Experiment 3 with the exception of the time interval pairs that were tested. The interval pairs in milliseconds (and their ratios) were as follows:

| | |
|---|---|
| 600-600 | (1:1) |
| 494-706 | (7:10) |
| 400-800 | (1:2) |
| 706-494 | (10:7) |
| 800-400 | (2:1) |

Comparison of the time interval pairs used in Experiments 3 and 4 reveals two important differences. In Experiment 3, the smallest interval in each pair always equaled 350 ms and the time ratio was varied by adjusting the duration of the larger interval. On the other hand, in the current experiment, the sum of intervals 1 and 2 was always 1200 ms and the time ratio was varied by adjusting the duration of both intervals. Past studies of imitation tasks that required continuous unimanual tapping (e.g., Povel, 1981) have tested sets of time interval pairs organized by the same logic and demonstrated that the relation between required time ratio and performance generalized across both types of arrangements. In Experiment 4, I sought to determine whether the same was true for discrete-trial unimanual tapping in the imitation and shaping tasks.

*Data Analysis*

The data for Experiment 4 was analyzed in the same way as Experiment 3.

I analyzed time intervals by assessing the probability that both intervals produced in the trials of a block fell within ±8.39% of their respective target intervals. The resulting interval ranges were

{366  400  434}

{453  494  536}

{550  600  650}

{647  706  765}

{733  800  867}.

Note the slight overlap between the allowable ranges for the 600 ms time interval and the 706 ms time interval. Also note the partial overlap between the allowable ranges for the 706 ms time interval and the 800 ms time interval.

I analyzed the time ratios by calculating the probability that the ratios, defined as interval 2 divided by interval 1, produced in the trials of a block fell within −15.48% to +18.32% of the ratio formed by the relevant target interval pair. These percentages were derived from the upper and lower limits of the allowable ranges associated with the target interval pairs. The allowable ranges for the ratios formed by the different target interval pairs did not overlap.

For purposes of data analysis, I placed the five target interval pairs into three groups: (a) the 1:1 pair (600-600 ms); (b) the 1:2 and 2:1 pairs (400-800 ms and 800-400 ms); and (c) the 7:10 and 10:7 pairs (494-706 ms and 706-494 ms).

For the shaping and imitation tasks separately, for each group of interval pairs, I calculated each participant's probability of success, averaged across trials 24 through 42, for producing the target interval pairs and for producing the associated ratios. I chose to analyze average performance for the last 19 trials in each block of trials (i.e., trials 24 to 42) because I thought the effects of shaping would be most apparent in these later trials. I analyzed the same set of trials for the imitation task in order to facilitate comparing performance between the imitation and shaping tasks.

In addition, for the shaping and imitation tasks separately, for each target interval pair, I calculated each participant's median produced time interval 1, median produced time interval 2, and median produced time ratio (interval 2 divided by interval 1), across trials 24 through 42.

## Results

The median produced time intervals 1 and 2, across trials 24 through 42, and the target interval pairs are shown in Tables 6 and 7 for the shaping task and imitation task respectively.

Table 6

*Experiment 4 Shaping Task -- Group Means (SD) of Median Produced Time Intervals for Trials 24 to 42*

| Target Interval Pair (ms) | Produced Intervals (ms) | |
|---|---|---|
| Interval 1:Interval 2 | Interval 1 | Interval 2 |
| 600:600 | 597 (77) | 549 (82) |
| 400:800 | 452 (64) | 644 (132) |
| 800:400 | 744 (132) | 479 (220) |
| 494:706 | 525 (82) | 585 (91) |
| 706:494 | 696 (119) | 500 (91) |

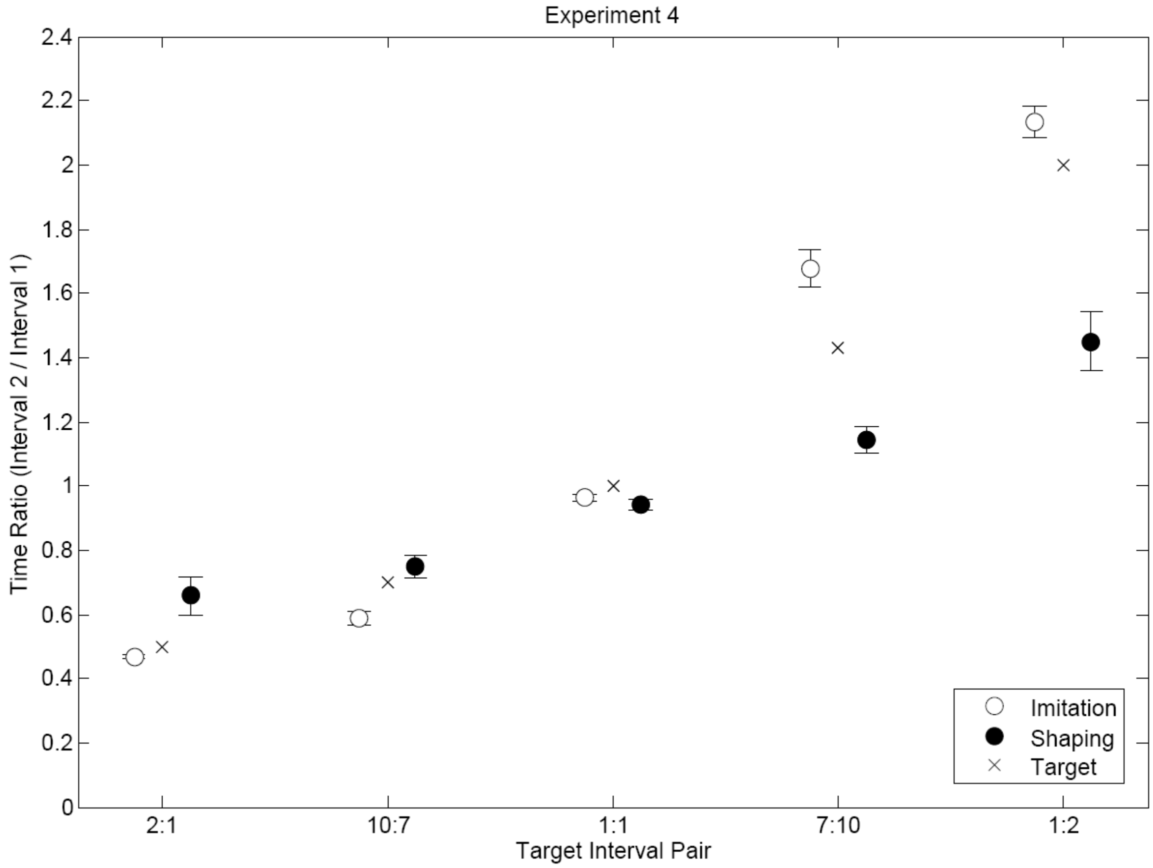
Table 7

*Experiment 4 Imitation Task -- Group Means (SD) of Median Produced Time Intervals for Trials 24 to 42*

| Target Interval Pair (ms) | Produced Intervals (ms) | |
|---|---|---|
| Interval 1:Interval 2 | Interval 1 | Interval 2 |
| 600:600 | 590 (41) | 567 (27) |
| 400:800 | 385 (20) | 820 (71) |
| 800:400 | 818 (64) | 381 (22) |
| 494:706 | 475 (66) | 775 (85) |
| 706:494 | 785 (116) | 457 (53) |

In the following, I report the analyses I did concerning the median produced time ratios, across trials 24 through 42, with task (shaping versus imitation) and target interval pair as the within-participants factors. I found a statistically significant main effect of task, $F(1, 19) = 44.03$, $p < .01$, characterized by average median produced time ratios of .99 for the shaping task and 1.17 for the imitation task. To put these two ratio values in context, I note that the average of the ratios formed by the five target interval pairs is 1.13. I also found a statistically significant effect of target interval pair, $F(4, 76) = 237.28$, $p < .01$. The time ratios formed by the target interval pairs and the median produced time ratios, averaged over the shaping and imitation tasks, for the 1:1, 1:2, 2:1, 7:10, and 10:7 conditions, were as follows: (a) 1, .9528; (b) 2, 1.7914; (c) .50, .5644; (d) 1.4286, 1.4092; and (e) .70, .6686. In addition, the interaction between task and target interval pair was significant, $F(4, 76) = 33.03$, $p < .01$.

As can be seen in Figure 12, for the shaping task, the mismatches between the produced time ratios and the time ratios formed by the target interval pairs generally increased as the latter ratios deviated from 1:1. Furthermore, the produced time ratios veered in the direction of 1:1. On the other hand, for the imitation task, the mismatches between the produced time ratios and the time ratios formed by the target interval pairs were the largest for the 7:10 and 10:7 conditions. Furthermore, the produced time ratios veered in the direction of 1:2 and 2:1 for the 7:10 and 10:7 target interval pairs, respectively.




| | | | | | |
|---|---|---|---|---|---|
| Ratio: | .47 **.50** .66 | .59 **.70** .75 | .96 **1.00** .94 | 1.68 **1.43** 1.14 | 2.13 **2.00** 1.45 |

**Figure 12.** Median produced time ratios, across trials 24 through 42, and the time ratios formed by the target interval pairs for the shaping and imitation tasks of Experiment 4. Black crosses represent the time ratios formed by the target interval pairs. White dots and black dots represent the means of the median produced time ratios for the imitation task and the shaping task respectively. Vertical bars denote ±1 standard error of the mean. In addition, the time ratios formed by the target interval pairs and the mean produced time ratios for the imitation task and the shaping task are displayed below the corresponding target interval pair on the x-axis of the graph. The time ratios formed by the target interval pairs are indicated in bold typeface and situated to the left and right respectively are the mean produced time ratios for the imitation and shaping tasks.

Figures 13 and 14 show the probability of accurately producing the time intervals and of accurately producing the time ratios, averaged over participants for each of the three groups of interval pairs, for the shaping and imitation tasks respectively. Produced time intervals were considered accurate or correct if both time intervals in a pair fell within ±8.39% of their respective target intervals. A produced time ratio was considered accurate or correct if it fell within −15.48% to +18.32% of the ratio formed by the relevant target interval pair. For the shaping task, the average points were fitted by power functions that characterized the increase in the probability of successful performance over practice (i.e., as a function of trial) for all groups of interval pairs.[6] On the other hand, for the imitation task, the average points were fitted by power functions that characterized the relatively constant probability of successful performance across trials for all groups of interval pairs.

[6] In trial 3, the average probability of accurately producing the time interval pair of the 1:1 interval-pair condition for the shaping task was zero. The power function was not fit to this data point for the 1:1 condition of the shaping task. In addition, in trials 2 and 3, the average probabilities of accurately producing the time interval pairs of the 7:10 and 10:7 interval-pair group for the shaping task were zero. The power function was not fit to these data points for the 7:10 and 10:7 group of the shaping task.

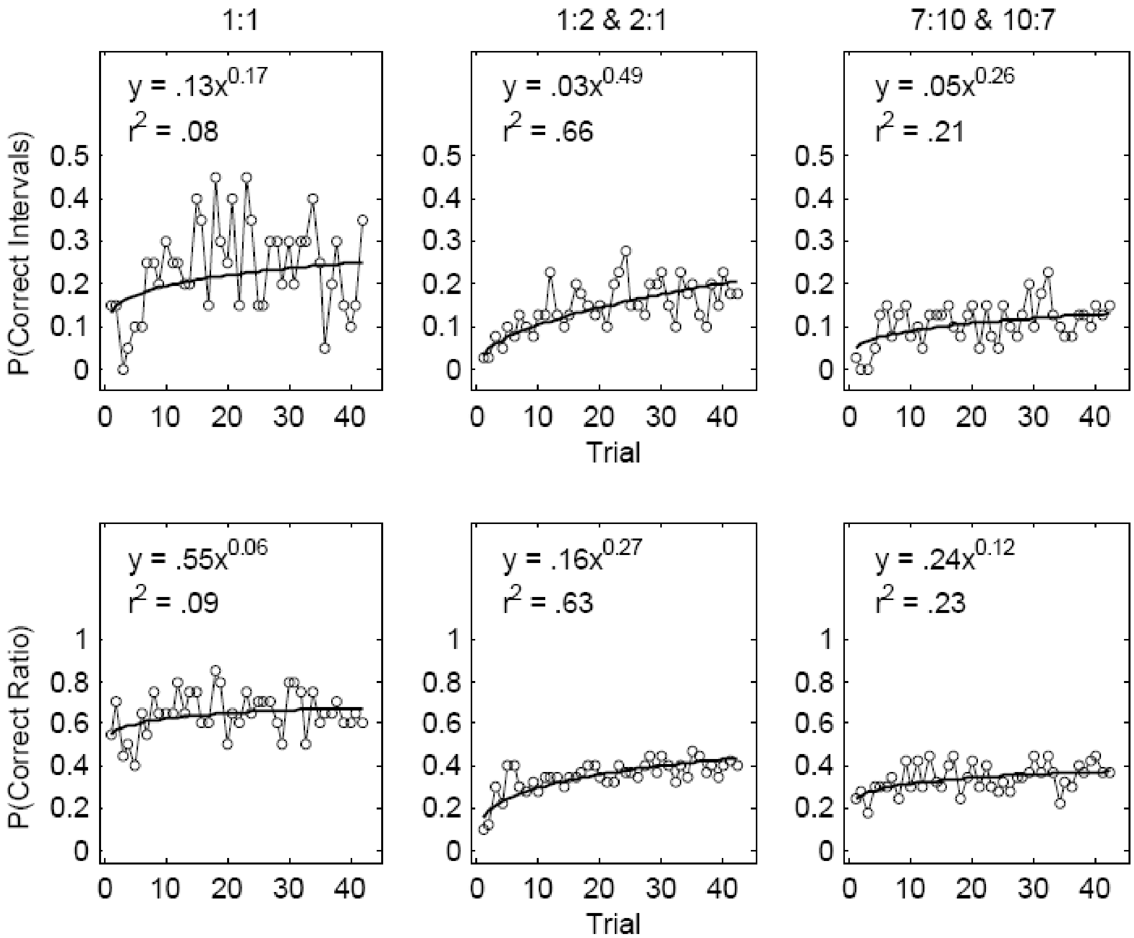



**Figure 13.** Probability of producing the target interval pairs (**top**) and probability of producing the ratios formed by the target interval pairs (**bottom**) averaged over participants for the three groups of interval pairs for the shaping task of Experiment 4. Power functions are fitted to all trials (i.e., trials 1 to 42).

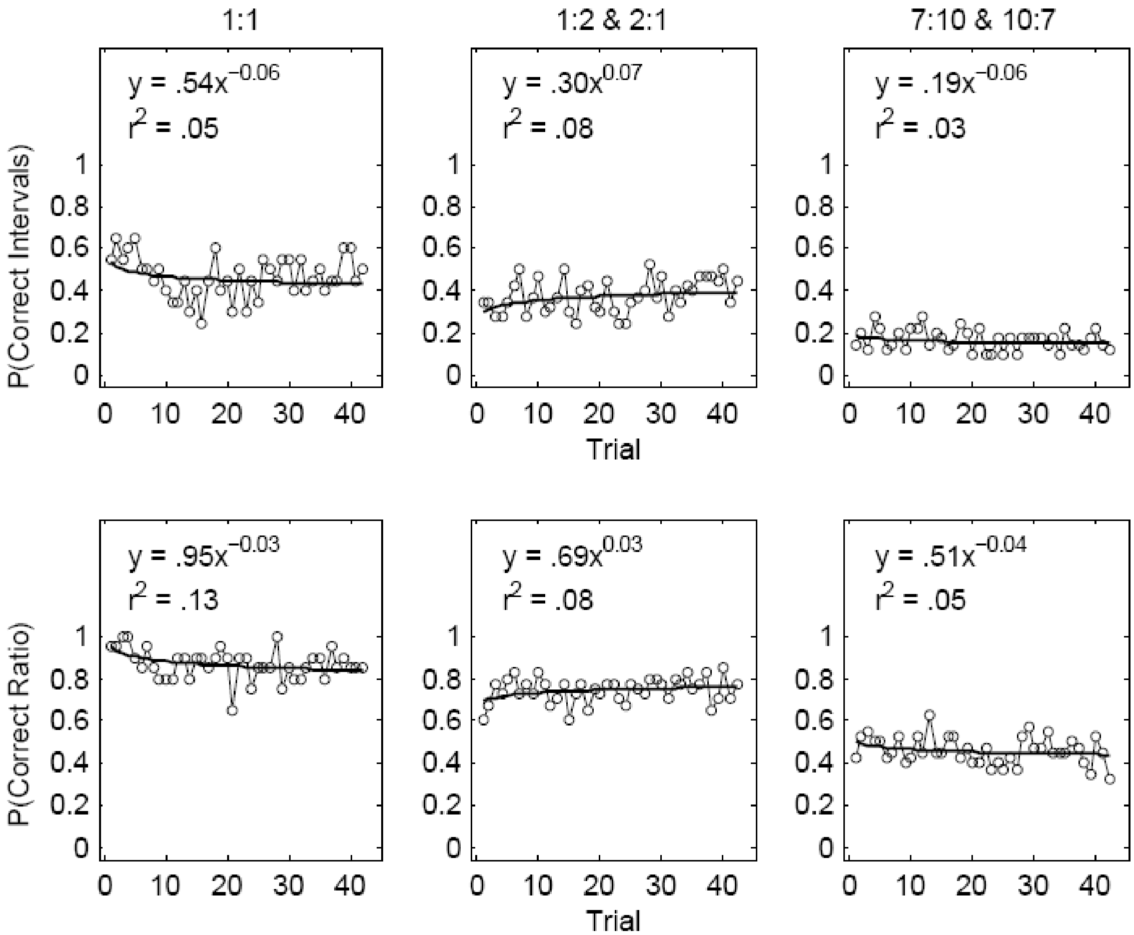



**Figure 14.** Probability of producing the target interval pairs (**top**) and probability of producing the ratios formed by the target interval pairs (**bottom**) averaged over participants for the three groups of interval pairs for the imitation task of Experiment 4. Power functions are fitted to all trials (i.e., trials 1 to 42).

In the analyses of time interval performance and time ratio performance that follow, I treated the three groups of interval pairs (i.e., 1:1 pair, 1:2 and 2:1 pairs, and 7:10 and 10:7 pairs) as three experimental conditions. This simplification was justified by confirming, via Tukey's Honestly Significant Difference method, that there were significant differences between the three groups for the shaping task and for the imitation task but never within either of the latter two groups (i.e., 1:2 and 2:1 pairs and 7:10 and 10:7 pairs), with all $p$ values exceeding .10 for the latter tests. This was confirmed for time interval performance and time ratio performance separately. I analyzed the probabilities of producing the target interval pairs, averaged across trials 24 through 42, with task (shaping versus imitation) and interval-pair group as the within-participants factors, and, in a second ANOVA, the probabilities of producing the ratios formed by the target interval pairs, with the same design. In the following, I report the analysis of time intervals first, followed by time ratios.

*Time Intervals*

I found a statistically significant main effect of task, $F(1, 19) = 13.32$, $p < .01$, characterized by a lower probability of success in the shaping task than in the imitation task. I also found a statistically significant effect of interval-pair group, $F(2, 38) = 19.56$, $p < .01$. The results of a Tukey's HSD Test indicated that: (a) the probability of success in the 1:2 and 2:1 conditions was not significantly less than in the 1:1 condition, $p > .10$; (b) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:1 condition, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:2 and 2:1 conditions, $p < .01$. In addition, the interaction between task and interval-pair group was significant, $F(2, 38) = 14.23$, $p < .01$.

As can be seen in Figure 11 (top center graph), the interaction can be characterized as larger differences between the performance levels of the imitation task and the shaping task for the 1:1, 1:2, and 2:1 conditions than the 7:10 and 10:7 conditions. These observations were confirmed via a Tukey's HSD Test. It was shown that: (a) the probability of success in the 1:1 condition was significantly less in the shaping task than in the imitation task, $p < .01$; (b) the probability of success in the 1:2 and 2:1 conditions was significantly less in the shaping task than in the imitation task, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was not significantly less in the shaping task than in the imitation task, $p > .10$.

As is also apparent in Figure 11 (top center graph), a second way of characterizing the interaction is that the shaping task resulted in three levels of performance, one for each interval-pair group. On the other hand, the imitation task resulted in only two levels of performance across the three interval-pair groups. More specifically, it appears that for the shaping task, the probability of success was highest for the 1:1 condition, lowest for the 7:10 and 10:7 conditions, and in-between for the 1:2 and 2:1 conditions. On the other hand, for the imitation task, Figure 11 (top center graph) suggests that performance levels were higher for the 1:1, 1:2, and 2:1 conditions than the 7:10 and 10:7 conditions, with similar levels of performance for the 1:1, 1:2, and 2:1 conditions. These observations were generally confirmed via a Tukey's HSD Test except for two comparisons indicated below. For the shaping task, it was shown that: (a) the probability of success in the 1:2 and 2:1 conditions was not significantly less than in the 1:1 condition, $p > .10$ (this result does not support the graphical observations); (b) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:1 condition, $p = .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was not significantly less than in the 1:2 and 2:1 conditions, $p > .10$ (this result does not support the graphical observations). For the imitation task, it was shown that: (a) the probability of success in the 1:2 and 2:1 conditions was not significantly less than in the 1:1 condition, $p > .10$; (b) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:1 condition, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:2 and 2:1 conditions, $p < .01$.

To summarize, the results indicated that participants produced time intervals more accurately in the imitation task than in the shaping task in the 1:1, 1:2, and 2:1 conditions but not in the 7:10 and 10:7 conditions. With regard to the shaping task, there was some indication that participants produced time intervals more accurately in the 1:1 condition than in the 1:2, 2:1, 7:10, and 10:7 conditions (although this reached statistical significance only for the 1:1 versus 7:10 and 10:7 comparison). There was also some indication that in the shaping task participants produced time intervals in the 1:2 and 2:1 conditions more accurately than in the 7:10 and 10:7 conditions, however this was not statistically significant. Finally, in the imitation task, participants produced time intervals more accurately in the 1:1, 1:2, and 2:1 conditions than in the 7:10 and 10:7 conditions, but participants did not produce time intervals more accurately in the 1:1 condition than in the 1:2 and 2:1 conditions.

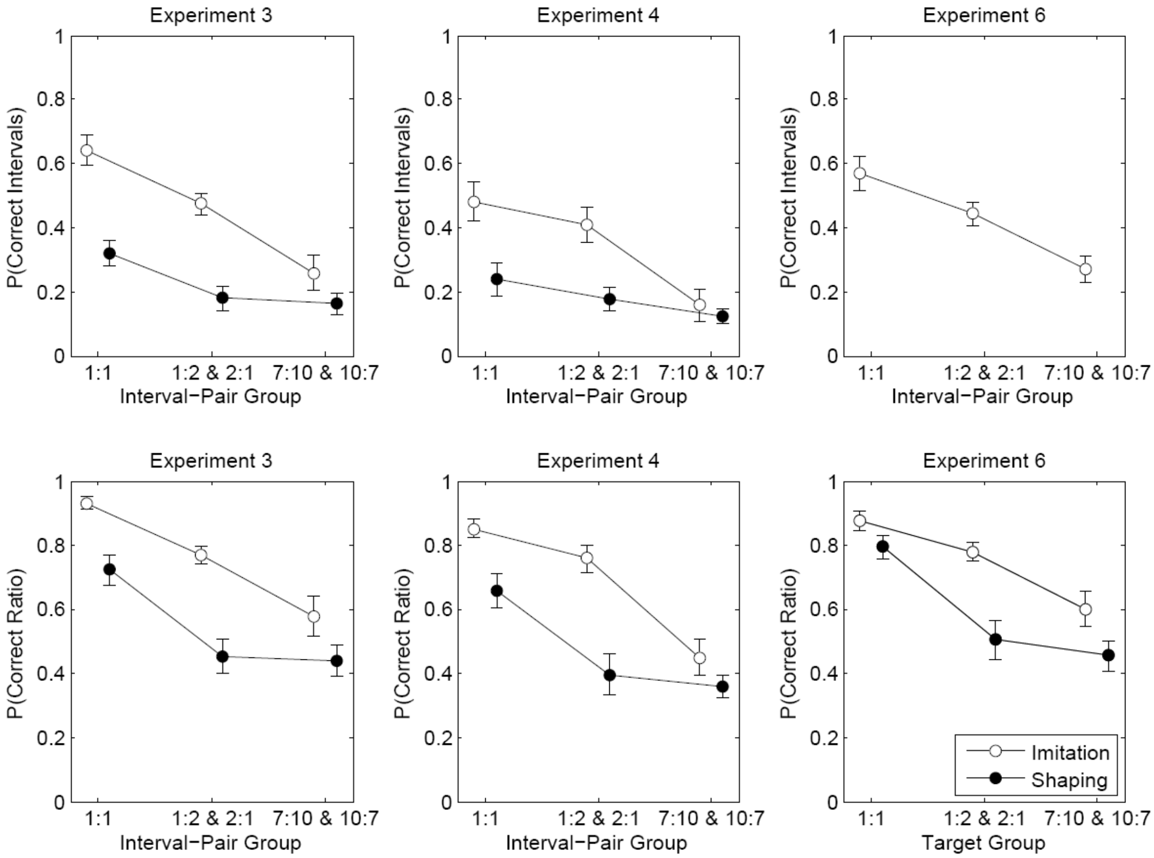



**Figure 11.** Probability of producing the target interval pairs (**top**), averaged across trials 24 through 42, and probability of producing the associated ratios (**bottom**), averaged across trials 24 through 42, for the three groups of interval pairs or target groups for Experiments 3, 4, and 6. Results for Experiments 3, 4, and 6 are displayed at the left, center, and right, respectively. White dots and black dots represent mean performances for the imitation tasks and the shaping tasks respectively. Vertical bars denote ±1 standard error of the mean.

*Time Ratios*

I found a statistically significant main effect of task, $F(1, 19) = 20.01$, $p < .01$, characterized by a lower probability of success in the shaping task than in the imitation task. I also found a statistically significant effect of interval-pair group, $F(2, 38) = 26.32$, $p < .01$. The results of a Tukey's HSD Test indicated that: (a) the probability of success in the 1:2 and 2:1 conditions was significantly less than in the 1:1 condition, $p < .01$; (b) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:1 condition, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:2 and 2:1 conditions, $p < .01$. In addition, the interaction between task and interval-pair group was significant, $F(2, 38) = 7.43$, $p < .01$.

As can be seen in Figure 11 (bottom center graph), the interaction can be characterized as larger differences between the performance levels of the imitation task and the shaping task for the 1:1, 1:2, and 2:1 conditions than the 7:10 and 10:7 conditions. These observations were confirmed via a Tukey's HSD Test. It was shown that: (a) the probability of success in the 1:1 condition was significantly less in the shaping task than in the imitation task, $p < .01$; (b) the probability of success in the 1:2 and 2:1 conditions was significantly less in the shaping task than in the imitation task, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was not significantly less in the shaping task than in the imitation task, $p > .10$.

As is also apparent in Figure 11 (bottom center graph), a second way of characterizing the interaction is that for the shaping task, performance levels were higher for the 1:1 condition than the 1:2, 2:1, 7:10, and 10:7 conditions, with no difference between the 1:2 and 2:1 conditions and the 7:10 and 10:7 conditions. On the other hand, for the imitation task, Figure 11 (bottom center graph) suggests that performance levels were higher for the 1:1, 1:2, and 2:1

conditions than the 7:10 and 10:7 conditions, with less of a difference between the 1:1 condition and the 1:2 and 2:1 conditions. These observations were confirmed via a Tukey's HSD Test. For the shaping task, it was shown that: (a) the probability of success in the 1:2 and 2:1 conditions was significantly less than in the 1:1 condition, $p < .01$; (b) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:1 condition, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was not significantly less than in the 1:2 and 2:1 conditions, $p > .10$. For the imitation task, it was shown that: (a) the probability of success in the 1:2 and 2:1 conditions was not significantly less than in the 1:1 condition, $p > .10$; (b) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:1 condition, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:2 and 2:1 conditions, $p < .01$.

To summarize, the results indicated that participants produced time ratios more accurately in the imitation task than in the shaping task in the 1:1, 1:2, and 2:1 conditions but not in the 7:10 and 10:7 conditions. With regard to the shaping task, participants produced time ratios more accurately in the 1:1 condition than in the 1:2, 2:1, 7:10, and 10:7 conditions, but participants did not produce time ratios more accurately in the 1:2 and 2:1 conditions than in the 7:10 and 10:7 conditions. Finally, in the imitation task, participants produced time ratios more accurately in the 1:1, 1:2, and 2:1 conditions than in the 7:10 and 10:7 conditions, but participants did not produce time ratios more accurately in the 1:1 condition than in the 1:2 and 2:1 conditions.

In the following analyses, I directly compared performance in the current experiment to performance in Experiment 3. I analyzed the probabilities of producing the target interval pairs, averaged across trials 24 through 42, with experiment (Experiment 3 versus Experiment 4) as the between-groups factor and interval-pair group as the within-participants factor, and, in a second ANOVA, the probabilities of producing the ratios formed by the target interval pairs, with the same design. In a third ANOVA I analyzed the median produced time ratios, across trials 24 through 42, with experiment (Experiment 3 versus Experiment 4) as the between-groups factor and target interval pair as the within-participants factor. I report the analyses for the shaping tasks first, followed by the imitation tasks.

*Comparison of Performance between the Shaping Tasks of Experiments 3 and 4*

*Time intervals.* For time interval performance the main effect of experiment was not statistically significant, $F(1, 38) = 1.04$, $p > .10$. I found a statistically significant effect of interval-pair group, $F(2, 76) = 11.07$, $p < .01$. The results of a Tukey's HSD Test indicated that: (a) the probability of success in the 1:2 and 2:1 conditions was significantly less than in the 1:1 condition, $p < .01$; (b) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:1 condition, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was not significantly less than in the 1:2 and 2:1 conditions, $p > .10$. The interaction between experiment and interval-pair group was not significant, $F(2, 76) = .85$, $p > .10$.

*Time ratios.* For time ratio performance the main effect of experiment was not statistically significant, $F(1, 38) = 1.91$, $p > .10$. I found a statistically significant effect of interval-pair group, $F(2, 76) = 24.14$, $p < .01$. The results of a Tukey's HSD Test indicated that: (a) the probability of success in the 1:2 and 2:1 conditions was significantly less than in the 1:1 condition, $p < .01$; (b) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:1 condition, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was not significantly less than in the 1:2 and 2:1 conditions, $p > .10$. The interaction between experiment and interval-pair group was not significant, $F(2, 76) = .03$, $p > .10$.

For median produced time ratios the main effect of experiment was not statistically significant, $F(1, 38) = 1.97$, $p > .10$. I found a statistically significant effect of target interval pair, $F(4, 152) = 89.03$, $p < .01$. The time ratios formed by the target interval pairs and the median produced time ratios, averaged over the shaping tasks of Experiments 3 and 4, for the 1:1, 1:2, 2:1, 7:10, and 10:7 conditions, were as follows: (a) 1, .9778; (b) 2, 1.4871; (c) .50, .6139; (d) 1.4286, 1.2499; and (e) .70, .7263. The interaction between experiment and target interval pair was marginally significant, $F(4, 152) = 2.40$, $p = .052$. As can be seen by comparing Figures 8 (p. 56) and 12 (p. 76), for the shaping tasks, the tendency for produced time ratios to veer in the direction of 1:1 was more pronounced in Experiment 4 than in Experiment 3.

To summarize, the results for time intervals and time ratios indicated that participants achieved similar levels of accuracy in the shaping tasks of Experiments 3 and 4 and produced similar time ratios.

*Comparison of Performance between the Imitation Tasks of Experiments 3 and 4*

*Time intervals.* For time interval performance I found a marginally significant effect of experiment, $F(1, 38) = 3.63$, $p = .06$, characterized by a lower probability of success in Experiment 4 than in Experiment 3. I found a statistically significant effect of interval-pair group, $F(2, 76) = 44.68$, $p < .01$. The results of a Tukey's HSD Test indicated that: (a) the probability of success in the 1:2 and 2:1 conditions was significantly less than in the 1:1 condition, $p < .01$; (b) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:1 condition, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:2 and 2:1 conditions, $p < .01$. The interaction between experiment and interval-pair group was not significant, $F(2, 76) = .81$, $p > .10$.

*Time ratios.* For time ratio performance I found a marginally significant effect of experiment, $F(1, 38) = 3.04$, $p = .09$, characterized by a lower probability of success in Experiment 4 than in Experiment 3. I found a statistically significant effect of interval-pair group, $F(2, 76) = 53.03$, $p < .01$. The results of a Tukey's HSD Test indicated that: (a) the probability of success in the 1:2 and 2:1 conditions was significantly less than in the 1:1 condition, $p < .01$; (b) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:1 condition, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:2 and 2:1 conditions, $p < .01$. The interaction between experiment and interval-pair group was not significant, $F(2, 76) = 1.24$, $p > .10$.

For median produced time ratios the main effect of experiment was not statistically significant, $F(1, 38) = .41$, $p > .10$. I found a statistically significant effect of target interval pair, $F(4, 152) = 774.61$, $p < .01$. The time ratios formed by the target interval pairs and the median produced time ratios, averaged over the imitation tasks of Experiments 3 and 4, for the 1:1, 1:2, 2:1, 7:10, and 10:7 conditions, were as follows: (a) 1, .9736; (b) 2, 2.1120; (c) .50, .4777; (d) 1.4286, 1.6278; and (e) .70, .6067. The interaction between experiment and target interval pair was not significant, $F(4, 152) = 1.22$, $p > .10$.

To summarize, the results for time intervals and time ratios indicated that participants achieved similar levels of accuracy in the imitation tasks of Experiments 3 and 4 (although there was some indication that participants were more accurate in Experiment 3 than Experiment 4) and produced similar time ratios.

## Discussion

The results of the shaping task used in Experiment 4 replicated the basic findings of the shaping task used in Experiment 3. The results generally indicated that 1:1 time ratios were easier to perform than the other ratios that I tested. However, I obtained no evidence that 1:2 and 2:1 time ratios were easier to perform than the 7:10 and 10:7 ratios. In addition, the results of the imitation task used in Experiment 4 generally replicated the basic findings of the imitation task used in Experiment 3. The results indicated that the 1:1, 1:2, and 2:1 time ratios were easier to perform than the 7:10 and 10:7 ratios. However, the 1:1 performance advantage (relative to performance in the 1:2 and 2:1 conditions) reached statistical significance in the imitation task of Experiment 3 but not in the imitation task of Experiment 4.

The results of Experiments 3 and 4 were similar despite the fact that the sets of time intervals tested in the two experiments differed in terms of the intervals themselves and the rules used to generate the interval pairs. This finding is consistent with the hypothesis that the relations between performance and required time ratios for the shaping and imitation tasks were independent of other properties of the sets of time intervals that were tested. Therefore, the current study demonstrated that the relation between performance and required time ratios generalized across different sets of required time-interval-pairs. Whereas this had already been shown for continuous-trial tapping (Povel, 1981), to the best of my knowledge, this is the first such demonstration for discrete-trial tapping.

## Chapter 6. EXPERIMENT 5

Experiment 5 and Experiment 6 were designed to test the plausibility of an alternative interpretation of the shaping results of Experiments 1, 3, and 4. This alternative interpretation stated that the reason KR eliminated the 1:2 and 2:1 interval-ratio advantages in the shaping tasks of Experiments 1, 3, and 4 was not that it took participants' focus off the real-time sensory events that accompanied their performance, but rather because the KR focused participants' attention on the time intervals themselves and not on the relation between the time intervals. Accordingly, if participants represented the time intervals independently, there is no reason to suspect that the relation between intervals (i.e., time ratio) should influence their performance. On the other hand, I reasoned that in the absence of KR, participants in the imitation tasks of Experiments 3 and 4 may have represented the relation between the time intervals in addition to the time intervals themselves. Even though Experiment 6 provided a more direct test of this hypothesis, I will report Experiment 5 first because it informed the design of Experiment 6.

In Experiment 5 I also employed a trial-and-error unimanual tapping procedure that provided participants with visual feedback (KR) after each trial. A key difference between this experiment and the previous experiments was that instead of providing KR for individual time intervals, I provided participants with KR for the ratio formed by adjacent time intervals (i.e., time interval 2 divided by time interval 1). I reasoned that providing participants with KR in terms of time ratios would focus their attention on the relation between the time intervals in addition to the time intervals themselves. Therefore, if the 1:2 and 2:1 advantages were eliminated in the shaping tasks of Experiments 1, 3, and 4 because the KR focused participants' attention on the time intervals and not on the relation between the time intervals, then it is reasonable to expect to see the 1:2 and 2:1 advantages in Experiment 5.

In addition to providing participants with KR in terms of time ratios, there are a number of other ways that the procedure used in Experiment 5 was different than the procedures used in the shaping tasks of Experiments 1, 3, and 4. For example, in Experiment 5 I conveyed the visual feedback (KR) to participants with a different type of display (discussed in more detail below) than was used in previous experiments. In the discussion section, I focus on how these procedural differences may have influenced the results.

## Method

### *Participants*

Twenty-one Penn State undergraduates (14 female and 7 male) participated for course credit. Eighteen participants were right-handed, two were left-handed, and one was ambidextrous. Participants reported musical training that ranged from no training at all to ten years training on a musical instrument. All participants were naive to the hypotheses. One participant, who was female and right-handed, did not complete the experiment due to problems understanding the instructions.

### *Apparatus*

Participants sat eye level with a Dell Ultrasharp 17 inch flat panel monitor (1280 x 1024 pixels) set 20 inches away on the desk. The experiment was conducted in a MATLAB-based environment on a Dell OptiPlex GX620 computer. Participants responded on a Dell RT7D50 keyboard.

### *Procedure and Design*

Participants were told that they would be producing time intervals by pressing the computer spacebar. In addition, participants were asked to keep the lower part of their hand in contact with the table so they made finger movements and not wrist movements.

Participants were informed that in each trial, they would be asked to produce two time intervals such that interval 2 was a particular percentage of interval 1. Participants were told that they would be provided with feedback to help them meet this expectation. Next, the experimenter presented the feedback display to the participant and explained its meaning. The feedback display consisted of three lines extending horizontally (see Figure 15). Participants were told that after the three finger taps were produced in a trial, a blue dot would appear on the display. It was explained that (a) a dot on the lower dashed line indicated that interval 2 was too small a percentage of interval 1, (b) a dot on the upper dashed line indicated that interval 2 was too large a percentage of interval 1, (c) a dot anywhere in the middle region of the display (above the lower dashed line and below the upper dashed line) indicated that interval 2 was an acceptable percentage of interval 1, and (d) the closer the dot was to the middle solid line of the display, the better the performance.

After receiving the task instructions, the participant was asked to state in his or her own words what the task was and what the feedback meant. The formal experiment began only after the experimenter was satisfied that the participant fully understood the task.

For a given target ratio, a participant completed 42 trials. Whenever the participant wished (i.e., with no time pressure to start), s/he produced two successive time intervals by pressing the computer spacebar three times. This was supposed to be done with the index finger of the dominant hand. When the spacebar was pressed for the third time, visual feedback was given about the ratio formed by the first produced interval (the time between the first press and the second) and the second produced interval (the time between the second press and the third). The time ratio was defined as interval 2 divided by interval 1. If the produced ratio fell within an accuracy band of ±14% of the target ratio, a blue dot appeared above or below the solid middle line at a distance that increased linearly with the difference of the produced ratio from the target ratio until a maximum difference was reached, whereupon the dot appeared on the top dashed line or bottom dashed line in the too-large or too-small outcomes, respectively. The accuracy band of ±14% of the target ratio was arrived at in pilot work. As the 42 trials went on, the feedback dot from the last performed trial remained on the screen but became a blue ring 1 s after its initial appearance as a blue dot.

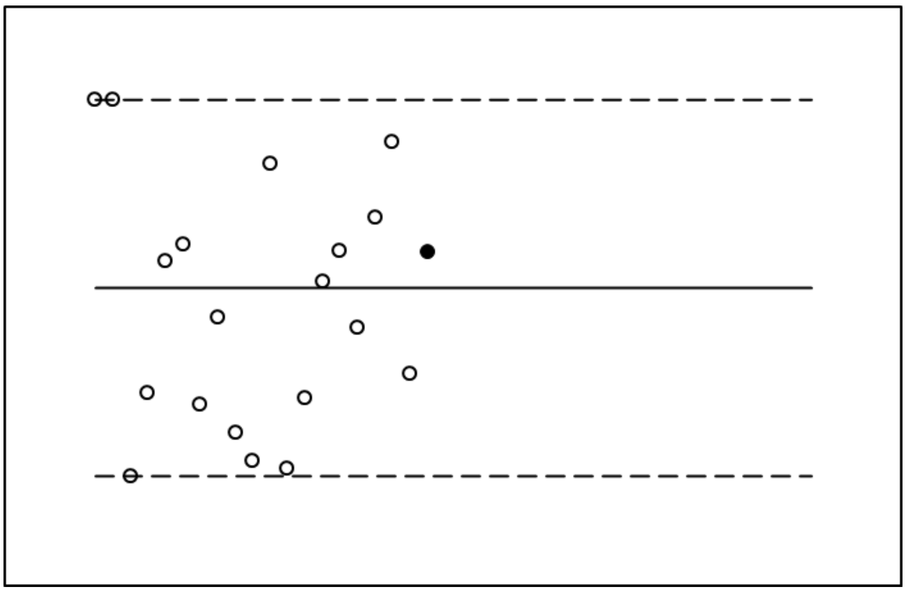


**Figure 15.** Experiment 5 feedback display from the first 20 trials (left to right) of a block of trials. The dot for the last completed trial is filled whereas the dots for the previously completed trials are empty. The smaller the vertical distance of a dot from the solid middle line, the closer the produced ratio was to the target ratio. The vertical distance between a dot and the solid middle line was linearly related to the signed difference of the produced ratio from the target ratio expressed as a proportion of the target ratio. Dots on the top or bottom dashed line equaled or exceeded a threshold difference of ±14% of the target ratio.

After a participant completed 42 trials, s/he was given end-of-block feedback about the average rectified difference between the required and generated ratios, expressed as a proportion of the required ratio, for that block and for each preceding block separately. I placed an upper limit on the value of this feedback measure such that it never exceeded 100%. This was done so participants would not be discouraged by a large average error that could potentially result from large differences between generated and required ratios on just a few trials. The participant was also reminded of his or her best score (i.e., the smallest average error for a previous block). The end-of-block feedback took the form of a bar graph and numbers on the computer screen. Participants were instructed to strive for ever-lower average errors (the smallest bars possible).

Each participant completed seven blocks of trials, with each block involving a unique target ratio. The ratios were 1:1, 1:2, 2:1, 2:3, 3:2, 2:5, and 5:2. For practice, each participant was randomly assigned one of the three target ratios that required a short interval followed by a long interval (1:2, 2:3, or 2:5) and one of the three target ratios that required a long interval followed by a short interval (2:1, 3:2, or 5:2). The order of presentation of the short-long and long-short target ratios was counterbalanced over participants. There were 32 trials in the two practice blocks. Participants were invited to take a 30 s break between the two practice blocks.

In the experiment, the full set of seven target ratios was presented to each participant. All participants were assigned the 1:1 target ratio in block 4. The remaining six target ratios were separated into two groups, short-long (i.e., 1:2, 2:3, or 2:5) and long-short (i.e., 2:1, 3:2, or 5:2). Each participant was assigned one of the two groups in a random order for blocks 1 through 3 and the other group in a random order for blocks 5 through 7. The order of presentation of the short-long and long-short target-ratio groups was counterbalanced across participants. I chose to group the target-ratio conditions in this manner, rather than randomly, so participants would not have to randomly switch between short-long and long-short target ratios. I thought such random switching might unnecessarily increase the difficulty of the task. Forty-two trials were completed for each of the seven experimental blocks. Participants were invited to take a 1 min break between the blocks.

*Data Analysis*

Performance was analyzed in terms of how accurately participants produced the target ratios. I defined the time ratio as interval 2 divided by interval 1. I analyzed time-ratio performance by calculating the probability that the ratios produced in the trials of a block fell within ±10% of their target ratio. The reason why I focused on this range was that it ensured that there was no overlap in the allowable ranges for the target ratios I tested. I calculated each participant's probability of success, averaged across trials 24 through 42, for producing the target ratios. I chose to analyze performance for the last 19 trials in each block of trials (i.e., trials 24 to 42) because I thought the effects of feedback would be most apparent in these later trials.

Initial observations of the data indicated a performance asymmetry: The probability of success, averaged over participants, was greater for the short-long target ratios and the 1:1 target ratio than it was for the long-short target ratios. Therefore, I chose to analyze the probability of successfully producing the short-long and long-short target-ratios separately by conducting two repeated-measures ANOVAs. The first ANOVA included the 1:2, 2:3, and 2:5 target ratios, whereas the second ANOVA included the 2:1, 3:2, and 5:2 target ratios. Analyzing the data in this way served two purposes. First, it allowed me to test for 1:2 and 2:1 performance advantages. Second, to anticipate, a subsequent analysis was predicated on finding no significant differences among the three short-long target ratios and among the three long-short target ratios. For this analysis, I placed the seven target ratios into three groups: (a) 1:1; (b) short-long (1:2, 2:3, and 2:5); and (c) long-short (2:1, 3:2, and 5:2). The probability of producing the target ratios for each group was submitted to a repeated-measures ANOVA with 1:1, short-long, and long-short target ratios as levels. This allowed me to test for performance advantages associated with 1:1, short-long, or long-short target ratios.

In addition, for each target ratio, I calculated each participant's median produced time interval 1, median produced time interval 2, and median produced time ratio (interval 2 divided by interval 1), across trials 24 through 42.

## Results

The median produced time intervals 1 and 2, across trials 24 through 42, and the target ratios are shown in Table 8. In addition, the median produced time ratios, across trials 24 through 42, and the target ratios are shown in Figure 16.

Figure 17 shows the probability of accurately producing the time ratios, averaged over participants and smoothed using a five-point weighted moving-average window for each of the seven target ratios.[7] A produced time ratio was considered accurate or correct if it fell within ±10% of its target ratio. The average points were fitted by power functions that characterized the increase in the probability of success as a function of trial number for all target ratios.

[7] The weights for the moving-average window as applied to trials three through forty were .1, .2, .4, .2, and .1. The weights as applied to trials 2 and 41 were .25, .5, and .25. The weights as applied to trials 1 and 42 were .5 and .5.

Table 8

*Experiment 5 -- Group Means (SD) of Median Produced Time Intervals for Trials 24 to 42*

| Target Ratio | Produced Intervals (ms) | |
|---|---|---|
| Interval 1:Interval 2 | Interval 1 | Interval 2 |
| 1:1 | 924 (532) | 896 (481) |
| 1:2 | 771 (558) | 1445 (993) |
| 2:1 | 1274 (586) | 667 (310) |
| 2:3 | 958 (633) | 1397 (949) |
| 3:2 | 1223 (629) | 867 (410) |
| 2:5 | 657 (415) | 1605 (1010) |
| 5:2 | 1604 (1033) | 698 (410) |

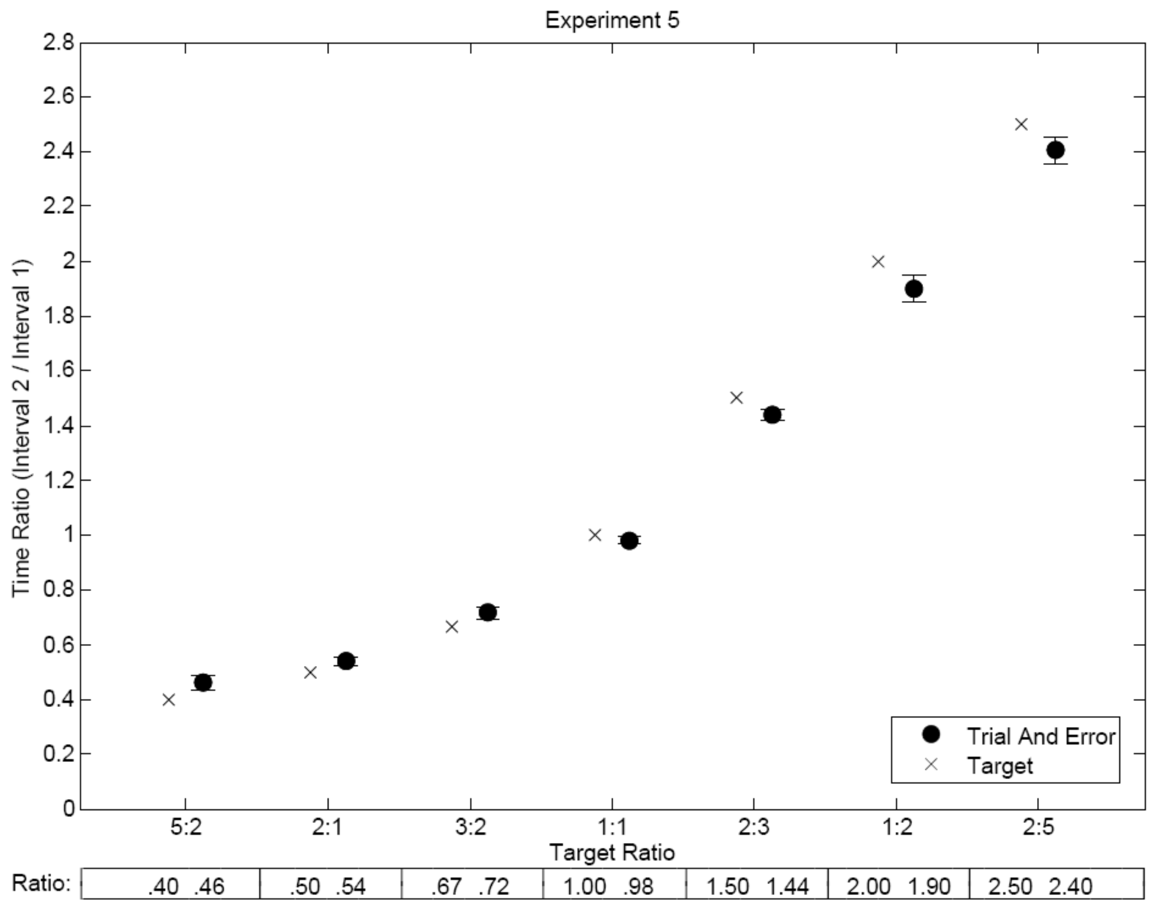



**Figure 16.** Median produced time ratios, across trials 24 through 42, and the target ratios of Experiment 5. Black crosses represent the target ratios and black dots represent the means of the median produced time ratios for the trial-and-error task. Vertical bars denote ±1 standard error of the mean. In addition, the target ratios and the mean produced time ratios for the trial-and-error task are displayed below and to the left and right respectively of the corresponding target ratio on the x-axis of the graph.

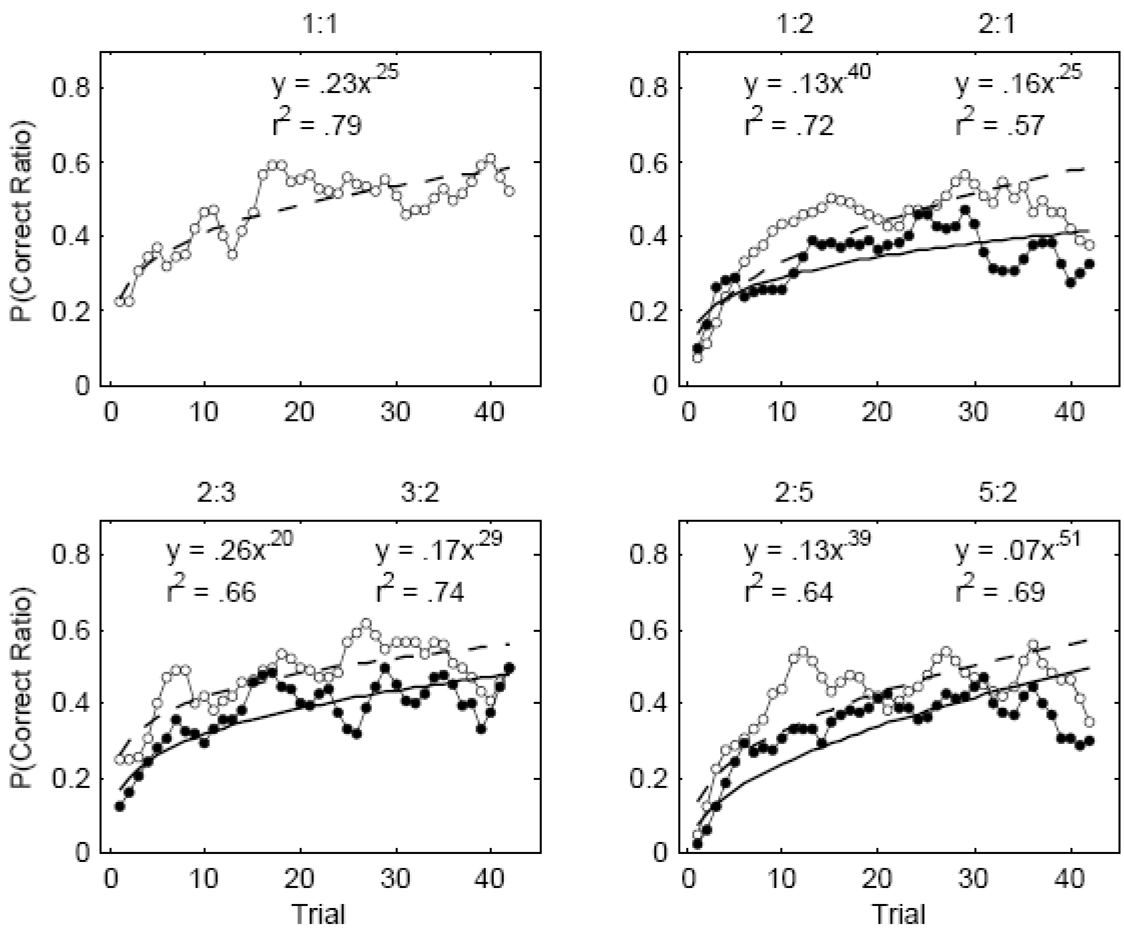



**Figure 17.** Probability of producing the target ratios averaged over participants and smoothed using a five-point weighted moving-average window for the seven target ratios of Experiment 5. White dots and black dots represent short-long and long-short target ratios respectively. Power functions are fitted to all trials (i.e., trials 1 to 42). Broken lines and solid lines represent the power functions for short-long and long-short target ratios, respectively.

In two ANOVAs, I analyzed the probabilities of producing the target ratios, averaged across trials 24 through 42, with target ratio as the within-participants factor. The first ANOVA included the 1:2, 2:3, and 2:5 target ratios as levels, whereas the second ANOVA included the 2:1, 3:2, and 5:2 target ratios as levels. No statistically significant main effects of target ratio were found for the short-long target ratios, $F(2, 38) = 1.05$, $p > .10$, or for the long-short target ratios, $F(2, 38) = .39$, $p > .10$. Thus, participants did not produce time ratios more accurately in the 1:2 and 2:1 conditions than in the corresponding complex conditions.

In the analysis that follows, I treated the three groups of target ratios (1:1, short-long, and long-short) as three experimental conditions. This simplification was justified by the previous analysis which showed that there were no significant differences within the short-long and long-short target-ratio groupings. I analyzed the probabilities of producing the target ratios, averaged across trials 24 through 42, with target-ratio group as the within-participant factor. This analysis revealed a statistically significant main effect of target-ratio group, $F(2, 38) = 9.53$, $p < .01$. The results of a Tukey's Honestly Significant Difference Test showed that: (a) the probability of success in the short-long target-ratio conditions (i.e., 1:2, 2:3, and 2:5) was not less than in the 1:1 condition, $p > .10$; (b) the probability of success in the long-short target-ratio conditions (i.e., 2:1, 3:2, and 5:2) was significantly less than in the 1:1 condition, $p < .01$; and (c) the probability of success in the long-short target-ratio conditions was significantly less than in the short-long conditions, $p < .01$. These results indicate that participants produced time ratios more accurately in the 1:1 condition and 1:2, 2:3, and 2:5 conditions than in the 2:1, 3:2, and 5:2 conditions, but did not produce time ratios more accurately in the 1:1 condition than in the 1:2, 2:3, and 2:5 conditions.

## Discussion

The results of this experiment did not provide clear evidence that 1:1 time ratios are special, at least not in the sense that 1:1 was produced more accurately than the other ratios. Instead, the results indicated that 1:1 ratios and the short-long ratios (i.e., 1:2, 2:3, and 2:5) were easier to perform than the long-short ratios (i.e., 2:1, 3:2, and 5:2). In addition, I obtained no evidence that 1:2 or 2:1 time ratios were easier to perform than the more complex ratios.

In the current experiment the 1:2 and 2:1 interval-ratio advantages were eliminated. This experiment was designed to focus participants' attention on the relation between the time intervals. Therefore, these results are not consistent with the hypothesis that the reason the 1:2 and 2:1 advantages were eliminated in the shaping tasks of Experiments 1, 3, and 4 was that participants focused on the time intervals themselves and not on the relation between the time intervals. If this were the case, it would be reasonable to have expected to see the 1:2 and 2:1 advantages in the current experiment.

In addition, to the best of my knowledge, this is the first demonstration of the 1:1 interval-ratio advantage being eliminated relative to performance in complex conditions such as 2:3 and 2:5. Although interesting, this result was unanticipated and does not directly speak to the hypothesis of the current experiment.

As mentioned earlier, there are a number of reasons to be cautious when interpreting the results of the current experiment in relation to the results of Experiments 1, 3, and 4. For example, while it is true that providing KR in terms of time ratios may have increased participants' focus on the relation between time intervals, this type of KR also allowed participants to choose the time intervals they produced. Furthermore, participants in the current experiment produced time intervals that were much longer than the time intervals that were produced in Experiments 1, 3, and 4. Table 8 (p. 97) presents median produced time intervals 1 and 2, for trials 24 through 42, for each target ratio of Experiment 5. Average time intervals ranged from approximately 650 to 1600 ms.

Previous research in equal interval tapping (Grondin, 1992) has shown that a strategy involving sub-dividing the produced interval into a number of internal counts can improve performance by reducing variability. Furthermore, it was shown that the optimal subdivision interval was approximately 400 ms (Grondin, 1992). Therefore, it follows that produced time intervals should be substantially larger than 400 ms to benefit from a counting strategy. In addition, a study of time perception showed that the accuracy of temporal judgments increased when participants used a counting strategy, especially when the presented time intervals were longer than approximately 1200 ms (Grondin, Meilleur-Wells, & Lachance, 1999). Therefore, the long duration of the time intervals produced in Experiment 5 suggests that the reason participants produced 1:1, 1:2, and the more complex time ratios (i.e., 2:3 and 2:5) equally well may have been that they used a counting strategy.

A second difference was that the KR that was provided to participants in the current experiment was more precise than the KR that was provided to participants in the shaping tasks of Experiments 1, 3, and 4. The feedback (KR) displays of Experiments 1, 3, and 4 and Experiment 5 are shown in Figures 2 (p. 20) and 15 (p. 93) respectively. Therefore, the greater precision of the KR in Experiment 5 may have played a role in participants producing 1:1, 1:2, 2:3, and 2:5 time ratios equally well.

A third way that the current experiment was different than Experiments 1, 3, and 4 was with regard to the order that the target conditions were presented to the participants. In Experiment 5 the three short-long (i.e., 1:2, 2:3, and 2:5) target ratio conditions and the three long-short (i.e., 2:1, 3:2, and 5:2) target ratio conditions were grouped together. Half the participants were presented with the three short-long target ratio conditions in a random order for blocks 1 through 3 and the three long-short target ratio conditions in a random order for blocks 5 through 7. The other half of the participants were presented with the short-long and long-short target ratio conditions in the reverse order. All participants in Experiment 5 were presented with the 1:1 target ratio for block 4. On the other hand, in Experiments 1, 3, and 4 the target interval pairs were presented to participants in a random order.

Holding the general structure of the target ratios (i.e., short-long or long-short) constant across consecutive blocks of trials may have made the task easier for participants than a situation in which the general structure of the target ratios varies randomly across blocks of trials. Therefore, the order that the target ratio conditions were presented to participants in Experiment 5 may have played a role in the 1:1, 1:2, 2:3, and 2:5 time ratios being produced equally well.

A question that remains is what caused long-short ratios to be more difficult than short-long ratios in Experiment 5? I will provide a speculative answer to this question in the following. The performance asymmetry observed in Experiment 5 may be attributable to the fact that I defined time ratio as time interval 2 divided by time interval 1 rather than time interval 1 divided by time interval 2. This definition of time ratio resulted in a <u>non</u>linear or inverse relation between produced time interval 1 and time ratio feedback (KR) and a linear relation between produced time interval 2 and time ratio feedback (KR). The theoretical relations between produced time interval 1 and time ratio feedback and produced time interval 2 and time ratio feedback are depicted in Figure 18.

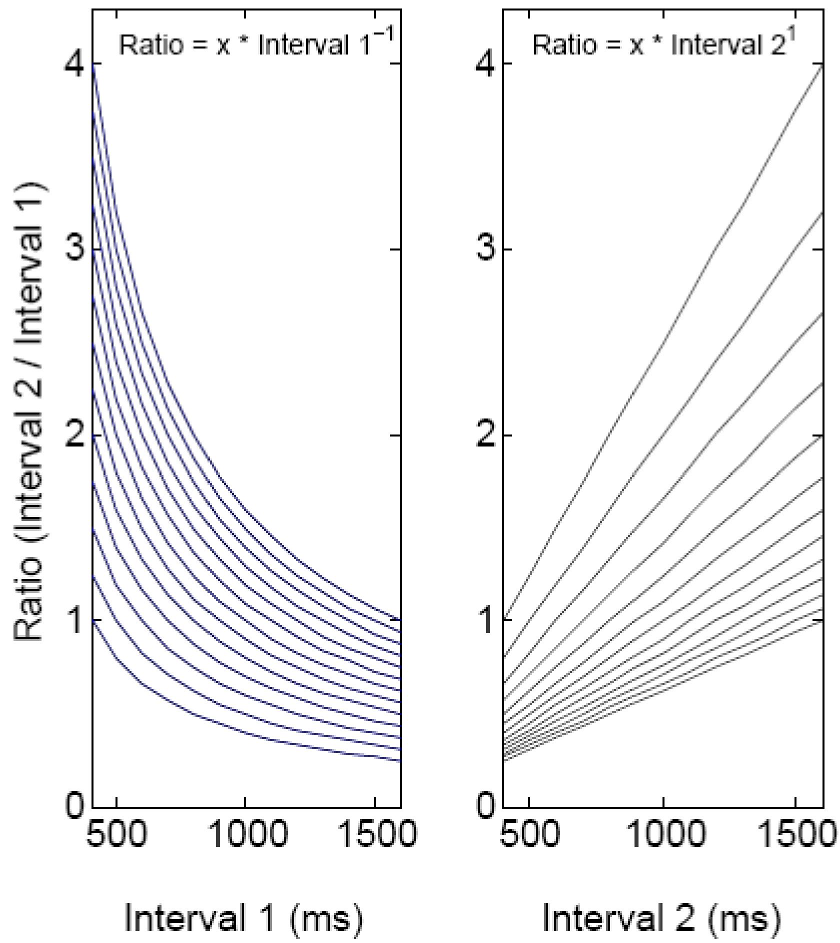



**Figure 18.** Theoretical relations between produced time interval 1 and time ratio feedback and produced time interval 2 and time ratio feedback. The left panel depicts the relation between time ratio and time interval 1 while time interval 2 is held constant at a number of different values. The right panel depicts the relation between time ratio and time interval 2 while time interval 1 is held constant at a number of different values.

During the experiment, the time intervals produced by participants varied during a block of trials and therefore the relation between the time ratio feedback that a participant received and his or her produced interval 1 was influenced by variation in both produced intervals 1 and 2 and similarly, the relation between time ratio feedback and produced interval 2 was influenced by variation in both produced intervals 1 and 2. I am speculating that if participants adopted a strategy in which they held the shorter required time interval approximately constant and responded to feedback by adjusting the longer required time interval, this would have resulted in a linear mapping between the time interval being adjusted and time ratio feedback for the short-long ratio conditions. On the other hand, this same strategy would have resulted in a <u>non</u>linear mapping between the time interval being adjusted and time ratio feedback for the long-short ratio conditions, the idea being that a nonlinear mapping may be harder for people to control. This possibility could be tested by running the same experiment and defining time ratio as time interval 1 divided by time interval 2 rather than time interval 2 divided by time interval 1 as it was defined for Experiment 5 feedback. The prediction is that the direction of the performance asymmetry observed in Experiment 5 should be reversed. That is, performance of long-short ratios should be better than short-long ratios.

On a more general note, the performance asymmetry of Experiment 5 bears some resemblance to the finding that participants' success in judging which of two time intervals is shorter and which is longer depends on the order in which the time intervals are presented (Allan, 1977; Allan & Gibbon, 1994). More specifically, when both time intervals are relatively long (e.g., 900 and 1000 ms), participants are more successful in their judgments when the shorter of the two intervals precedes the longer interval than when the order of presentation is reversed. In other words, participants are more adept at identifying a short-long interval sequence as short-long than identifying a long-short interval sequence as long-short. This effect has been attributed to perceptual processes as well as decision processes (Allan, 1977).

## Chapter 7. EXPERIMENT 6

Experiment 6 was designed to provide a more direct test of the hypothesis that the reason the 1:2 and 2:1 interval-ratio advantages were eliminated in the shaping tasks of Experiments 1, 3, and 4 was that participants focused on the time intervals themselves and not on the relation between the time intervals. I tested this hypothesis by having participants perform in a discrete-trial shaping task similar to the one described in Experiment 3 with the exception that KR was provided for time interval ratios instead of time intervals. I provided participants with KR in terms of time ratios to focus their attention on the relation between the time intervals in addition to the time intervals themselves. I also had participants perform in a discrete-trial imitation task identical to the one described in Experiment 3. Regarding the imitation task, I reasoned that due to the absence of KR, participants may naturally represent the relation between the time intervals in addition to the time intervals themselves. The hypothesis would be supported if the 1:2 and 2:1 advantages were observed in the imitation task and the shaping task.

### Method

*Participants*

Twenty healthy people (12 female and 8 male) participated in this experiment. Nineteen participants were Penn State students who participated for course credit or were recruited by placing flyers around the campus and paid $9. The remaining participant was recruited via a flyer and paid $9; this individual had a bachelor’s degree, but was not a student at the time of the experiment. Eighteen participants were right-handed and two were left-handed. Participants reported musical training that ranged from no training whatsoever to six years training on a musical instrument including voice [this information was obtained via question 3 of the Ollen

Musical Sophistication Index Questionnaire (Ollen, 2006)]. All participants were naive to the hypotheses, and none had been in any of the previous experiments.

*Apparatus*

The apparatus was the same as in Experiment 3.

*Procedure and Design*

The procedures for the shaping and imitation tasks were identical to Experiment 3, with the exception that in the current shaping task, feedback was provided for time interval ratio instead of time intervals, as was the case for Experiment 3.

The sequence of events for an individual trial in the shaping task is shown in Figure 19. In the shaping procedure, a participant saw two open circles arrayed horizontally on a computer screen. Whenever the participant wished (i.e., with no time pressure to start), s/he produced two successive time intervals by pressing the computer spacebar three times with the index finger of his or her dominant hand. When the spacebar was pressed for the first time, the left circle immediately filled in. When the spacebar was pressed for the second time, nothing changed on the screen. When the spacebar was pressed for the third time, visual feedback was given about the ratio formed by the first produced interval (the time between the first press and the second) and the second produced interval (the time between the second press and the third). The time ratio was defined as interval 2 divided by interval 1. The feedback about the time ratio was associated with the right circle and it remained on the computer screen for one second.

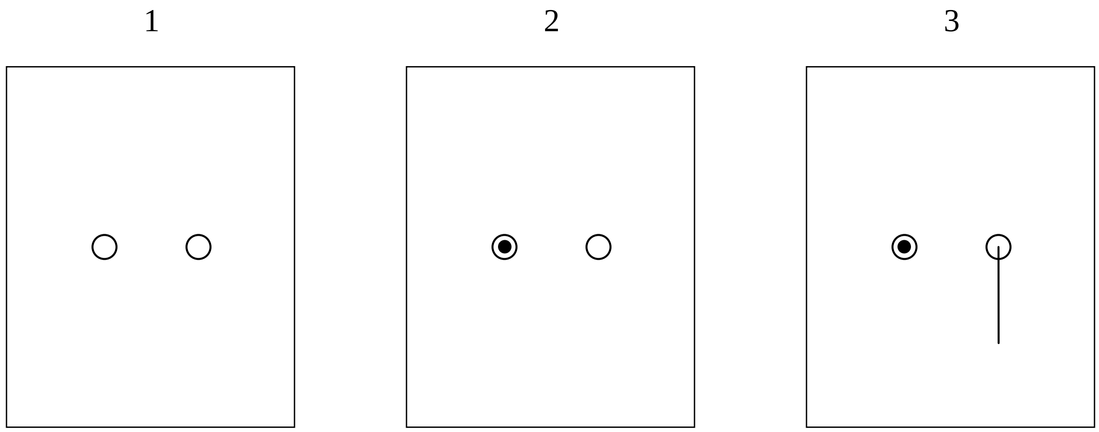



**Figure 19.** Feedback display for the shaping task of Experiment 6. **(1)** Initial screen appears 1 sec after completion of previous trial. **(2)** Participant begins timing interval 1 by pressing the spacebar, whereupon a green dot appears. A second spacebar-press completes interval 1 and begins interval 2, and a third spacebar-press completes interval 2. **(3)** After completion of interval 2, feedback is shown at right for the time interval ratio (i.e., interval 2 divided by interval 1). The feedback shown here indicates that the ratio was too small.

There were three possible forms of visual feedback for the ratio. If the produced ratio fell within a currently prescribed accuracy band, a blue dot filled the right circle. If the produced ratio was too large relative to the currently prescribed accuracy band, a line of fixed length extended up from the right circle. If the produced ratio was too small relative to the currently prescribed accuracy band, a line of fixed length extended down from the right circle. Because the length of the line was fixed, its length provided no information about the extent of overshoot or undershoot.

The accuracy band for a ratio started at −22.47% to +28.98% of each target ratio. These percentages were derived from the upper and lower limits of the starting accuracy bands for time intervals (i.e., ±12.66%) used in Experiment 3. If a participant achieved correct trials on at least 2 out of 3 consecutive trials, the accuracy band was reduced by approximately 25%.

Participants were instructed to get as many trials correct as possible in a block of trials. After a participant completed 42 trials, s/he was given end-of-block feedback regarding the number of correct trials for that block. The participant was also reminded of his or her best score (i.e., the highest number of correct trials for a previous block). The end-of-block feedback took the form of numbers on the computer screen.

In addition to the shaping task, participants performed in an imitation task. Half the participants performed the shaping task first followed by the imitation task and the other half of the participants performed the two tasks in the reverse order.

For the imitation task of this experiment, I tested the same set of time-interval pairs as in Experiment 3. The interval pairs in milliseconds (and their ratios) were as follows:

| | |
|---|---|
| 350-350 | (1:1) |
| 350-500 | (7:10) |
| 350-700 | (1:2) |
| 500-350 | (10:7) |
| 700-350 | (2:1) |

For the shaping task, the same time interval ratios were tested as in the imitation task. During shaping, upper and lower limits of 1100 and 300 ms were imposed on the allowable time intervals. During the task, if produced time intervals 1 or 2 exceeded either of these thresholds, the participant was notified in a feedback display immediately after the trial. This feedback took the form of words on the computer screen which remained there until the participant pressed the spacebar to begin the next trial. On these trials, the participant did not receive feedback about the accuracy of the produced time ratio. In addition, participants were required to repeat these trials until the requisite number of trials was met for that block.

For the shaping and imitation tasks, each participant completed five blocks of trials, with each block testing a unique target ratio or target interval pair respectively. Each participant was randomly assigned three of the five target conditions for practice. Five trials were completed for each of the three practice blocks. In the experiment, the full set of five target interval pairs (imitation task) or target ratios (shaping task) were presented to each participant in a different random order for each participant. In the experiment, forty-two trials were completed for each block.

*Data Analysis*

For the shaping task, for each target ratio, I calculated the number of trials that were rerun due to participants exceeding the upper and lower time interval limits of 1100 and 300 ms. On a related note, all other analyses of the shaping task that I present in the following were based on the 42 trials per target ratio that each participant produced that did not involve time interval limit violations.

For the imitation task, I calculated the probability of producing the target interval pairs using the same accuracy criteria as in Experiment 3. I analyzed <u>time intervals</u> by assessing the probability that both intervals produced in the trials of a block fell within ±8.39% of their respective target intervals. This percentage ensured that the allowable ranges for different target intervals did not overlap.

I calculated the probability of producing the target ratios for the shaping task and the probability of producing the ratios formed by the target interval pairs for the imitation task using the same accuracy criteria as in Experiment 3. I analyzed the <u>time ratios</u> by calculating the probability that the ratios, defined as interval 2 divided by interval 1, produced in the trials of a block fell within −15.48% to +18.32% of the relevant target ratio (shaping task) or the ratio formed by the relevant target interval pair (imitation task). These percentages were derived from the upper and lower limits of the allowable ranges associated with the target interval pairs from the imitation task. Critically, the allowable ranges for different target ratios (shaping task) and for the ratios formed by different target interval pairs (imitation task) did not overlap.

For purposes of data analysis, I placed the five target interval pairs (imitation task) or target ratios (shaping task) into three groups: (a) the 1:1 pair (350-350 ms); (b) the 1:2 and 2:1 pairs (350-700 ms and 700-350 ms); and (c) the 7:10 and 10:7 pairs (350-500 ms and 500-350 ms).

For the shaping task, for each group of target ratios, I calculated each participant's probability of success, averaged across trials 24 through 42, for producing the target ratios. I chose to analyze average performance for the last 19 trials in each block of trials (i.e., trials 24 to 42) because I thought the effects of shaping would be most apparent in these later trials.

For the imitation task, for each group of interval pairs, I calculated each participant's probability of success, averaged across trials 24 through 42, for producing the target interval pairs and for producing the associated ratios. I analyzed trials 24 to 42 in order to facilitate comparing performance between the imitation and shaping tasks.

In addition, for the shaping and imitation tasks separately, for each target ratio (shaping task) or target interval pair (imitation task), I calculated each participant's median produced time interval 1, median produced time interval 2, and median produced time ratio (interval 2 divided by interval 1), across trials 24 through 42.

## Results

In the following analysis of the number of time interval limit violations for the shaping task, I treated the three groups of target ratios (i.e., 1:1 ratio, 1:2 and 2:1 ratios, and 7:10 and 10:7 ratios) as three experimental conditions. This simplification was justified by confirming, via Tukey's Honestly Significant Difference method, that there were significant differences between the three groups but never within either of the latter two groups (i.e., 1:2 and 2:1 ratios and 7:10 and 10:7 ratios), with all $p$ values exceeding .10 for the latter tests.

I found a statistically significant effect of target-ratio group, $F(2, 38) = 4.78$, $p = .01$. The three target-ratio groups and their average number of time interval limit violations were as follows: (a) 1:1 target ratio, 3.2 violations; (b) 1:2 and 2:1 target-ratio group, 7.4 violations; and (c) 7:10 and 10:7 target-ratio group, 5.6 violations. The results of a Tukey's HSD Test indicated that: (a) the number of time interval limit violations in the 1:1 condition was significantly less than in the 1:2 and 2:1 conditions, $p = .01$; (b) the number of time interval limit violations in the 1:1 condition was not significantly less than in the 7:10 and 10:7 conditions, $p > .10$; and (c) the number of time interval limit violations in the 7:10 and 10:7 conditions was not significantly less than in the 1:2 and 2:1 conditions, $p > .10$.

The median produced time intervals 1 and 2, across trials 24 through 42, and the target ratios (shaping task) or target interval pairs (imitation task) are shown in Tables 9 and 10 for the shaping task and imitation task respectively.

Table 9

*Experiment 6 Shaping Task -- Group Means (SD) of Median Produced Time Intervals for Trials 24 to 42*

| Target Ratio | Produced Intervals (ms) | |
|---|---|---|
| Interval 1:Interval 2 | Interval 1 | Interval 2 |
| 1:1 | 507 (152) | 508 (151) |
| 1:2 | 463 (134) | 737 (122) |
| 2:1 | 679 (182) | 387 (50) |
| 7:10 | 551 (184) | 702 (167) |
| 10:7 | 577 (122) | 446 (84) |

Table 10

*Experiment 6 Imitation Task -- Group Means (SD) of Median Produced Time Intervals for Trials 24 to 42*

| Target Interval Pair (ms) | Produced Intervals (ms) | |
|---|---|---|
| Interval 1:Interval 2 | Interval 1 | Interval 2 |
| 350:350 | 354 (23) | 356 (18) |
| 350:700 | 345 (19) | 691 (54) |
| 700:350 | 703 (54) | 341 (16) |
| 350:500 | 341 (23) | 535 (78) |
| 500:350 | 546 (37) | 336 (24) |

In the following, I report the analyses I did concerning the median produced time ratios, across trials 24 through 42, with task (shaping versus imitation) and target condition as the within-participants factors. In the results that follow, I use the term “target condition” to refer to the target ratios of the shaping task and the target interval pairs of the imitation task. I found a statistically significant main effect of task, $F(1, 19) = 5.85$, $p < .05$, characterized by average median produced time ratios of 1.08 for the shaping task and 1.14 for the imitation task. To put these two ratio values in context, I note that the average ratio associated with the five target conditions is 1.13. I also found a statistically significant effect of target condition, $F(4, 76) = 295.36$, $p < .01$. The time ratios associated with the target conditions and the median produced time ratios, averaged over the shaping and imitation tasks, for the 1:1, 1:2, 2:1, 7:10, and 10:7 conditions, were as follows: (a) 1, 1.0123; (b) 2, 1.8222; (c) .50, .5508; (d) 1.4286, 1.4405; and (e) .70, .7076. In addition, the interaction between task and target condition was significant, $F(4, 76) = 19.89$, $p < .01$.

As can be seen in Figure 20, for the shaping task, the mismatches between the produced time ratios and the target time ratios generally increased as the latter ratios deviated from 1:1. Furthermore, the produced time ratios veered in the direction of 1:1. On the other hand, for the imitation task, the mismatches between the produced time ratios and the time ratios formed by the target interval pairs were the largest for the 7:10 and 10:7 conditions. Furthermore, the produced time ratios veered in the direction of 1:2 and 2:1 for the 7:10 and 10:7 target interval pairs, respectively.

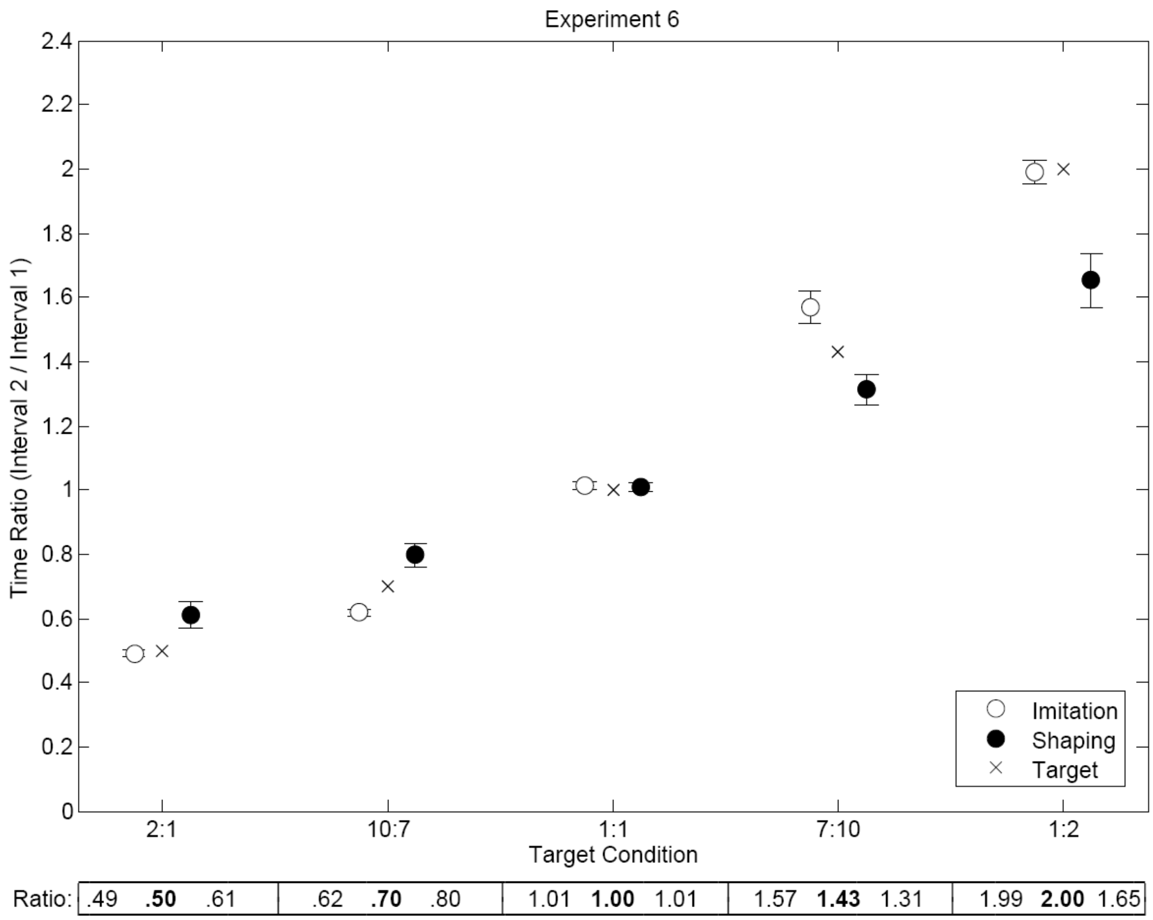



**Figure 20.** Median produced time ratios, across trials 24 through 42, and the time ratios associated with the target conditions for the shaping and imitation tasks of Experiment 6. Black crosses represent the time ratios associated with the target conditions. White dots and black dots represent the means of the median produced time ratios for the imitation task and the shaping task respectively. Vertical bars denote ±1 standard error of the mean. In addition, the time ratios of the target conditions and the mean produced time ratios for the imitation task and the shaping task are displayed below the corresponding target condition on the x-axis of the graph. The time ratios of the target conditions are indicated in bold typeface and situated to the left and right respectively are the mean produced time ratios for the imitation and shaping tasks.

Figure 21 shows the probability of accurately producing the time ratios, averaged over participants for each of the three groups of target ratios, for the shaping task. A produced time ratio was considered accurate or correct if it fell within −15.48% to +18.32% of its target ratio. The average points were fitted by power functions that characterized the increase in the probability of successful performance over practice (i.e., as a function of trial) for all groups of target ratios.

Figure 22 shows the probability of accurately producing the time intervals and of accurately producing the time ratios, averaged over participants for each of the three groups of target interval pairs, for the imitation task. Produced time intervals were considered accurate or correct if both time intervals in a pair fell within ±8.39% of their respective target intervals. A produced time ratio was considered accurate or correct if it fell within −15.48% to +18.32% of the ratio formed by the relevant target interval pair. For the imitation task, the average points were fitted by power functions that characterized the relatively constant probability of successful performance across trials for all groups of target interval pairs. In the following, I report the analysis of time intervals first, followed by time ratios.

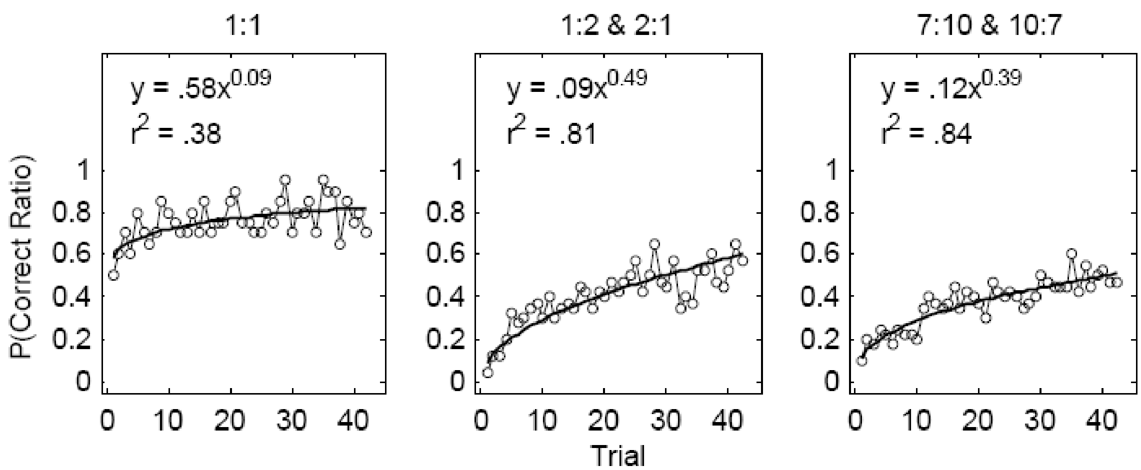



**Figure 21.** Probability of producing the target ratios averaged over participants for the three groups of target ratios for the shaping task of Experiment 6. Power functions are fitted to all trials (i.e., trials 1 to 42).

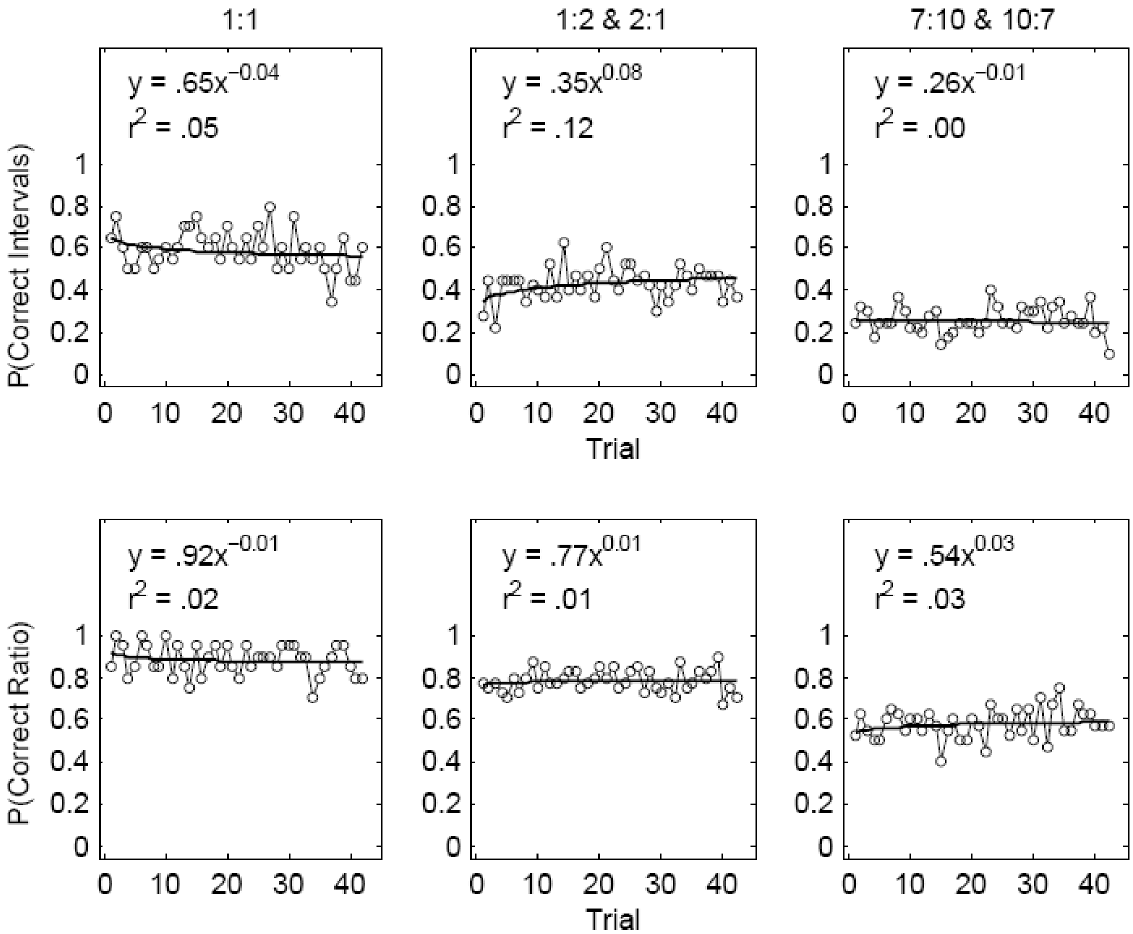



**Figure 22.** Probability of producing the target interval pairs (**top**) and probability of producing the ratios formed by the target interval pairs (**bottom**) averaged over participants for the three groups of interval pairs for the imitation task of Experiment 6. Power functions are fitted to all trials (i.e., trials 1 to 42).

*Time Intervals*

In the following analysis of time interval performance for the imitation task, I treated the three groups of target interval pairs (i.e., 1:1 pair, 1:2 and 2:1 pairs, and 7:10 and 10:7 pairs) as three experimental conditions. This simplification was justified by confirming, via Tukey's Honestly Significant Difference method, that there were significant differences between the three groups but never within either of the latter two groups (i.e., 1:2 and 2:1 pairs and 7:10 and 10:7 pairs), with all $p$ values exceeding .10 for the latter tests. I analyzed the probabilities of producing the target interval pairs, averaged across trials 24 through 42, with interval-pair group as the within-participants factor.

I found a statistically significant effect of interval-pair group, $F(2, 38) = 19.70$, $p < .01$. The results of a Tukey's HSD Test indicated that: (a) the probability of success in the 1:2 and 2:1 conditions was significantly less than in the 1:1 condition, $p < .05$; (b) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:1 condition, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:2 and 2:1 conditions, $p < .01$. Time interval performance for the three interval-pair groups in the imitation task of Experiment 6 is depicted in Figure 11 (top right graph).

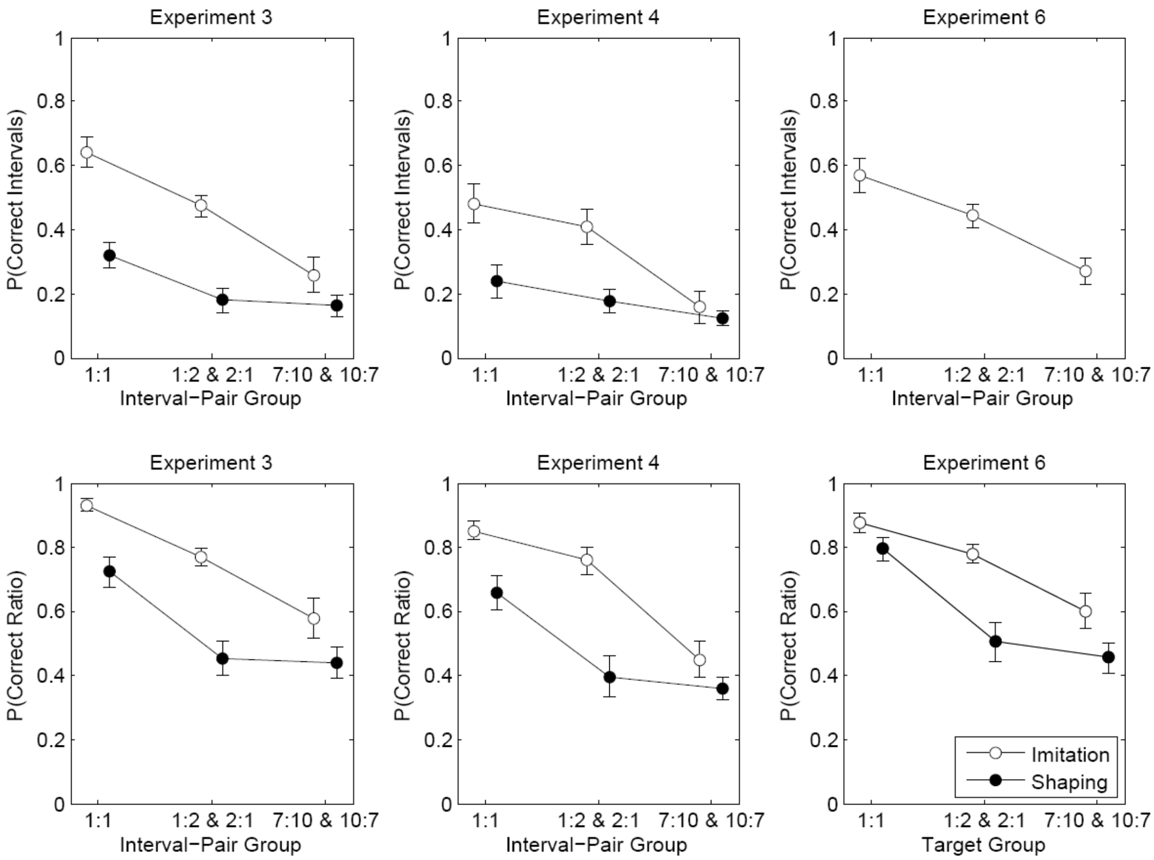



**Figure 11.** Probability of producing the target interval pairs (**top**), averaged across trials 24 through 42, and probability of producing the associated ratios (**bottom**), averaged across trials 24 through 42, for the three groups of interval pairs or target groups for Experiments 3, 4, and 6. Results for Experiments 3, 4, and 6 are displayed at the left, center, and right, respectively. White dots and black dots represent mean performances for the imitation tasks and the shaping tasks respectively. Vertical bars denote ±1 standard error of the mean.

*Time Ratios*

In the following analysis of time ratio performance for the shaping and imitation tasks, I treated the three groups of target ratios (shaping task) or target interval pairs (imitation task) (i.e., 1:1 pair, 1:2 and 2:1 pairs, and 7:10 and 10:7 pairs) as three experimental conditions. This simplification was justified by confirming, via Tukey's Honestly Significant Difference method, that there were significant differences between the three groups for the shaping task and for the imitation task but never within either of the latter two groups (i.e., 1:2 and 2:1 pairs and 7:10 and 10:7 pairs), with all $p$ values exceeding .10 for the latter tests. I analyzed the probabilities of producing the target ratios (shaping task) and the probabilities of producing the ratios formed by the target interval pairs (imitation task), averaged across trials 24 through 42, with task (shaping versus imitation) and target group as the within-participants factors. In the following, I use the term "target group" to refer to the target-ratio groups of the shaping task and the interval-pair groups of the imitation task.

I found a statistically significant main effect of task, $F(1, 19) = 14.81$, $p < .01$, characterized by a lower probability of success in the shaping task than in the imitation task. I also found a statistically significant effect of target group, $F(2, 38) = 42.56$, $p < .01$. The results of a Tukey's HSD Test indicated that: (a) the probability of success in the 1:2 and 2:1 conditions was significantly less than in the 1:1 condition, $p < .01$; (b) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:1 condition, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:2 and 2:1 conditions, $p < .01$. In addition, the interaction between task and target group was significant, $F(2, 38) = 3.91$, $p < .05$.

As can be seen in Figure 11 (bottom right graph), the interaction can be characterized as larger differences between the performance levels of the imitation task and the shaping task for the 1:2, 2:1, 7:10, and 10:7 conditions than the 1:1 condition. These observations were confirmed via a Tukey's HSD Test. It was shown that: (a) the probability of success in the 1:1 condition was not significantly less in the shaping task than in the imitation task, $p > .10$; (b) the probability of success in the 1:2 and 2:1 conditions was significantly less in the shaping task than in the imitation task, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was marginally less in the shaping task than in the imitation task, $p = .06$.

As is also apparent in Figure 11 (bottom right graph), a second way of characterizing the interaction is that the shaping task resulted in only two levels of performance across the three target groups (i.e., target-ratio groups) whereas the imitation task resulted in three levels of performance, one for each target group (i.e., interval-pair group). More specifically, it appears that for the shaping task, performance levels were higher for the 1:1 condition than the 1:2, 2:1, 7:10, and 10:7 conditions, with no difference between the 1:2 and 2:1 conditions and the 7:10 and 10:7 conditions. On the other hand, for the imitation task, Figure 11 (bottom right graph) suggests that the probability of success was highest for the 1:1 condition, lowest for the 7:10 and 10:7 conditions, and in-between for the 1:2 and 2:1 conditions. These observations were generally confirmed via a Tukey's HSD Test except for one comparison indicated below. For the shaping task, it was shown that: (a) the probability of success in the 1:2 and 2:1 conditions was significantly less than in the 1:1 condition, $p < .01$; (b) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:1 condition, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was not significantly less than in the 1:2 and 2:1 conditions, $p > .10$. For the imitation task, it was shown that: (a) the probability of success in the

1:2 and 2:1 conditions was not significantly less than in the 1:1 condition, $p > .10$ (this result does not support the graphical observations); (b) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:1 condition, $p < .01$; and (c) the probability of success in the 7:10 and 10:7 conditions was significantly less than in the 1:2 and 2:1 conditions, $p = .01$.

To summarize, the results indicated that participants produced time ratios more accurately in the imitation task than in the shaping task in the 1:2 and 2:1 conditions but not in the 1:1 condition. There was also some indication that participants produced time ratios more accurately in the imitation task than in the shaping task in the 7:10 and 10:7 conditions, although this result just missed reaching statistical significance. With regard to the shaping task, participants produced time ratios more accurately in the 1:1 condition than in the 1:2, 2:1, 7:10, and 10:7 conditions, but participants did not produce time ratios more accurately in the 1:2 and 2:1 conditions than in the 7:10 and 10:7 conditions. Finally, in the imitation task, participants produced time ratios more accurately in the 1:1, 1:2, and 2:1 conditions than in the 7:10 and 10:7 conditions, but participants did not produce time ratios more accurately in the 1:1 condition than in the 1:2 and 2:1 conditions.

## Discussion

Performance in the shaping and imitation tasks of Experiment 6 was similar to performance in the shaping and imitation tasks of Experiment 3. Similar performances were found for the shaping tasks of Experiments 3 and 6 despite the fact that participants were provided with KR in terms of time intervals in Experiment 3 and time interval ratios in Experiment 6. Critically, the 1:2 and 2:1 interval-ratio advantages were eliminated in the shaping task of Experiment 6. This result is not consistent with the hypothesis that the reason the 1:2 and

2:1 advantages were eliminated in the shaping tasks of Experiments 1, 3, and 4 was that participants focused on the time intervals themselves and not on the relation between the time intervals. If this were the case, it would be reasonable to have expected to see the 1:2 and 2:1 advantages in the shaping task of Experiment 6 because it was designed to focus participants' attention on the relation between the time intervals.

Alternatively, the reason that the 1:2 and 2:1 advantages were eliminated in the shaping task of the current experiment may have been that participants were too focused on the time intervals and not focused enough on the relation between the time intervals. This may have been the case because in addition to receiving KR in terms of time ratios, participants were notified when they exceeded upper and lower time interval limits (i.e., 300 and 1100 ms).

# Chapter 8. GENERAL DISCUSSION

In this study, I inquired into the nature of the representational factors involved in the control of unimanual finger tapping. The strategy I used to address this question was based on the idea that it is plausible that different methods for inducing motor output (e.g., shaping task versus imitation task) engage various information processes (e.g., short-term memory, long-term memory, decision processes, etc.) to different degrees. The information processes that are thought to be engaged by a particular method for inducing motor output can then be related to performance. Similar approaches that associate task variations with different information processes have been taken by motor control researchers (e.g., Rosenbaum, Dawson, & Challis, 2006) and by researchers interested in better understanding the information processes involved in time-perception tasks (e.g., Rodriguez-Girones & Kacelnik, 2001; Wearden & Bray, 2001).

The results of the current study provide support for the idea that the 1:2 and 2:1 interval-ratio advantages in unimanual tapping are a reflection of perceptual biases. More specifically, I presented evidence consistent with the hypothesis that the source of the 1:2 and 2:1 interval-ratio advantages is internal representations based on real-time sensory events associated with target performance. In other words, the results can be taken to suggest that the 1:2 and 2:1 interval-ratio advantages are a reflection of how tapping sounds, looks, and or feels. I accomplished this by demonstrating that the 1:2 and 2:1 advantages were observed in tasks that did not provide participants with knowledge of results or KR (i.e., imitation tasks and a continuation task) and eliminated in tasks that provided participants with KR (i.e., shaping tasks). Previous research in motor learning (Salmoni, Schmidt, & Walter, 1984; Winstein, 1991; Wulf & Schmidt, 1989) has suggested that participants base their internal representations on real-time sensory information when they are not provided with KR and that participants do not base their internal representations on real-time sensory information when they are provided with KR.

On the other hand, the results of the current study indicated that the 1:1 interval-ratio advantage may have more than one contributing factor. The fact that the 1:1 advantage was observed in the imitation tasks and the continuation task can be taken to suggest that the source of this advantage is internal representations based on real-time sensory events associated with target performance (i.e., how tapping sounds, looks, and or feels). However, because a 1:1 advantage was also observed in the shaping tasks, I conclude that this advantage may also stem from cognitive efficiencies associated with replicating a single time interval rather than producing two different time intervals, as required for all other interval ratios.

In addition, the current study demonstrated that the influence that required time-interval-ratios had on performance in the shaping and imitation tasks was largely independent of other properties of the sets of time intervals that were tested. I accomplished this by showing that the relations between performance and required time-interval-ratios were similar in two experiments (i.e., Experiments 3 and 4) that tested the same time interval ratios while using different sets of time interval pairs. The sets of time intervals that were tested in Experiments 3 and 4 differed in terms of the intervals themselves and the rules used to generate the interval pairs.

Finally, I presented evidence that did not support an alternative explanation of why KR eliminated the 1:2 and 2:1 interval-ratio advantages in the shaping tasks of the current study. This alternative explanation stated that the reason KR eliminated the 1:2 and 2:1 advantages was that it was presented in terms of time intervals thereby causing participants to focus exclusively on the time intervals and not on the relation between the time intervals. Accordingly, if time intervals were represented independently, there is no reason to suspect that the relation between intervals (i.e., time interval ratio) should influence performance. Contrary to this explanation, the 1:2 and 2:1 advantages were eliminated in a shaping task (i.e., Experiment 6) that was designed to focus participants' attention on the relation between the time intervals in addition to the time intervals themselves. This was accomplished by providing KR in terms of the ratio formed by adjacent time intervals (i.e., time interval 2 divided by time interval 1).

More generally, the current study demonstrated different time-interval-ratio biases for unimanual tapping between tasks that had participants use the same effector (i.e., index finger) but used different methods to induce motor output (i.e., shaping tasks versus imitation tasks). In contrast, previous studies (Semjen & Ivry, 2001; Summers et al., 1989) have demonstrated similar time-interval-ratio biases for tapping tasks that had participants use different effectors (e.g., one index finger, both index fingers, or index finger and middle finger of the same hand) but used the same method to induce motor output (i.e., imitation task). These findings suggest that time-interval-ratio biases in tapping tasks are more closely linked to the method used to induce motor output than the effector/s used by the participant. This observation is consistent with a theoretical point of view that argues for the importance of representational factors in controlling rhythmic movements.

Additional hypotheses regarding the role of particular information processes in the simple interval-ratio advantages could be tested by future studies that vary the method used to induce motor output. For example, in the discussion of Experiment 3, I suggested that a hypothesis regarding the involvement of long-term memory in the 1:2 and 2:1 interval-ratio advantages could be tested with a variation of the imitation tasks used in the current study in which the time interval pair to be imitated varies randomly from trial-to-trial within a block. In addition to providing information about how simple movements are controlled, the knowledge gained from this type of study may inform future attempts at understanding the processes involved in controlling more complex movements that are vital in daily life.

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**Journal Articles:**

- van der Wel, R., **Eder, J.**, Mitchel, A., Walsh, M., & Rosenbaum, D. (2009). Trajectories emerging from discrete versus continuous processing models in phonological competitor tasks: A commentary on Spivey, Grosjean, and Knoblich (2005). *Journal of Experimental Psychology: Human Perception and Performance, 35*(2), 588-594.

**Presentations At Meetings:**

- **Eder, J. R.** & Rosenbaum, D. A. (March, 2010). *Is the simple interval-ratio advantage in unimanual tapping due to error detection or error correction?* Talk presented at the 20th annual New England Sequencing and Timing Conference, New Haven, Connecticut.

- **Eder, J. R.** & Rosenbaum, D. A. (November, 2009). *Trial-and-error learning eliminates the simple interval-ratio advantage for unimanual tapping*. Poster presented at the 50th annual meeting of the Psychonomic Society, Boston, Massachusetts.

- **Eder, J. R.** & Rosenbaum, D. A. (November, 2008). *Shaping eliminates the simple interval-ratio advantage for unimanual tapping*. Poster presented at the 49th annual meeting of the Psychonomic Society, Chicago, Illinois.

- **Eder, J. R.** (June, 2007). *A perception-action cycle as a model of pink noise in continuation tapping.* Talk presented at the Third International Workshop on Posture-Based Motion Planning, University Park, PA.

- Slifkin, A., Bethoux, F., Stough, D., Charlotte, M., Bialko, C., & **Eder, J.** (June, 2007). *Mental practice of action and rehabilitation of multiple sclerosis.* Poster presented at the 12th Annual ACTRIMS Meeting, Washington, DC.

- Slifkin, A. B., **Eder, J. R.**, & Hamilton, R. L. (November, 2004). *Noise in Fitts' Law: White Time and Pink Space.* Talk presented at the 45th annual meeting of the Psychonomic Society, Minneapolis, Minnesota.

**Extramural Service:**

- Manuscript review for Acta Psychologica (May, 2010)