



## The intrinsic link between motor behavior and temporal cognition

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### A B S T R A C T

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The debate about the cognitive mechanisms behind human temporal processing has raged for decades without a clear resolution. The theory presented here describes a different perspective to the traditional accounts on the issue, namely, that motor behaviors or sequences of motor behaviors provide a means of reproducing time intervals. Evidence behind this perspective includes tapping strategies (exemplified by musicians), counting strategies, and neuropsychological results showing activation of motor areas during temporal cognitive tasks. I propose that motor behaviors aid human timing by offering a set of processes that consistently take a set amount of time to accomplish. Motor behaviors also allow segmentation of larger intervals into smaller intervals that are easier to estimate. I conclude with a discussion of implications of this perspective on temporal cognition.

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One of the more interesting debates in cognitive psychology is the nature of temporal cognition. Temporal cognition is a set of skills in humans and animals that mentally compute time intervals and here is used to encompass tasks including temporal production (i.e., behaviorally marking a time interval) or temporal estimation (i.e., communicating the perceived length of an interval by itself or in comparison with other intervals). Temporal cognitive researchers agree that there is an internal timekeeper that measures time (see Wearden, 1991), but they disagree with the form that this timekeeper takes.

One set of researchers (e.g., Port, 2003) believes that the timekeeper is a set of oscillators with each oscillator producing a unique beat. The beats can be arranged in a host of different combinations to reproduce one interval. Error within each of these oscillating mechanisms contributes to the overall duration estimation error.

Another set of researchers (e.g., Church & Broadbent, 1990) believes that the internal timekeeper is more like a clock. It has a single small unit of time, analogous to a clock's second-long beats that can reproduce any interval

length larger than one of these beats. Error results from random beat interval errors from the clock.

Once either the clock timekeeper or the set of oscillators issues a pulse, it sends that pulse through an attentional gate and into an accumulator (Gibbon, Church, & Meck, 1984). The accumulator counts the number of pulses that occurred since the start of the process. This mechanism allows measurement of longer intervals than a simple set of oscillators or a limited number of ticks from the clock can calculate.

In order to perform even the most simple of temporal tasks, tapping a one-to-one rhythm (i.e., the same interval between beats), the above scenario involves too many complex calculations. In the case of oscillators, some process sorts through dozens of oscillators to find the right combination of oscillation frequency to reproduce the beat interval from the environment (i.e., entrainment, see Jones & Boltz, 1989). In the case of the clock model, the single unit of time is so small (to cover very small intervals) that longer intervals must involve many ticks and a counting mechanism must have enough computational power to keep track of large numbers. The accumulator at the end of the process must also keep track of how many beats occurred, which is a very computationally heavy calculation.

I describe a less complicated theory on the cognitive system used for measuring time. Instead of a timekeeper that issues pulses to an accumulator which undergoes

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complex, covert calculations, people and animals use motor behaviors and motor imagery to entrain to intervals in the environment. Although this theory differs significantly from more traditional theories, it also draws from other research. The theory is similar to that of Killeen and Fetterman (1988) and Shaffer (1982), though unlike their theories which included traditional timekeepers, the present theory includes no internal timekeeper apart from the one implemented by the cognitive motor system. In the next several paragraphs, I outline how this process may occur. Then, I discuss evidence for this phenomenon from everyday life, from temporal cognitive research, and from neuropsychological evidence. I conclude by discussing ways to improve interval timing in individual and group tasks and by summarizing the strengths of the motor–temporal link theory.

## 1. How motor behaviors are conducive to timing

Ecological psychology (Gibson, 1979) outlines an approach to perception that stands out from most other theories of perception. According to Gibson (1979), perception is guided and aided by action. For example, people improve accuracy when measuring an object's weight and height by moving the object through space rather than just holding or viewing the object (Turvey, Solomon, & Burton, 1989).

The present approach to temporal cognition is similar to the ecological perspective, but instead of judging weight or height, individuals use motor behavior to judge the passage of time. We do this by performing motor behaviors to match intervals in the environment. According to this perspective, the timing of the motor behaviors themselves provides a mechanism for measuring time intervals and not a hypothesized set of timing mechanisms, such as a mental timekeeper, an accumulator, or a set of counting processes.

This account of the theory is not meant to imply that there is a general temporal cognition which may be covered by a generalization of movements. Instead each interval to be approximated represents an individual problem to be mentally calculated with stored behaviors. Though oscillators represent an internal timekeeper in his theory, Bickhard (2009) presents a similar theory of temporal cognition by suggesting that each interval is unique and requires different means of representation.

### 1.1. Movement parameters

Zatsiorski (1998) finds that motor behavior is represented and reproduced with precise kinematic parameters including velocity. Velocity is the relation of two components: distance and time. The proprioceptive sense is so finely tuned that it can locate body position and detect minute position changes in any part of the body (van Beers, Sittig, & Denier van der Gon, 1998). This gives the motor system a method of judging distance and change in distance (i.e., velocity).

Velocity and acceleration are calculated by the brain-motor system (see Zatsiorski, 1998). Muscle contraction patterns applied to certain bodily effectors (i.e., body parts controlled by voluntary muscles) will cause them to move

with specific movement trajectories with given speeds. The weight of these effectors and their length determine the force required to move with certain distance and velocity parameters. These parameters are stored in the cognitive motor system (see Kawato, 1999).

In velocity and acceleration equations, a set value for distance, velocity, and acceleration leave only one parameter unspecified – time. If all other parameters are held constant, then the time interval of the actions will always be the same. The cognitive motor system is designed to reduce the change in acceleration over time (i.e., jerk) to minimal whenever possible (Flash & Hogan, 1985), so jerk should not factor into these equations unless something goes wrong in motor execution.

Lee (1976) discusses Tau theory which would seem to contradict the usefulness of discussing movement parameters. Instead, Lee suggests that the eyes directly perceive movement by sensing the size of an object as it changes in the individual's perspective (this would presumably include the size of bodily effectors). However, Tresilian (1999) provides a strong critique of Lee's theory, pointing out that this type of direct perception can only be applied to fast-moving (so that the shifts in perceived size exceed just noticeable differences quickly), entirely spherical objects that do not accelerate or decelerate. Tresilian's common sense critique of Lee's Tau theory provides convincing support for the use of movement parameters in timed action.

### 1.2. Motor memory

Research suggests that memory for motor action is conducive to choosing motor behaviors that initially estimate time and adapting those initial motor behaviors. Keele (1968) suggests that the cognitive motor system stores patterns of motion in memory for later execution.

Gielen, van der Oosten, and Pull ter Gunne (1985) found that participants produced approximately the same acceleration and velocity for the same movements, which leads to the conclusion that both velocity and acceleration are stored in motor memory. Motor memories are specific in the amount of force that should be applied in the muscles but also adjust to environmental conditions. For example, locomotion (i.e., walking or running) is characterized by a gait that depends on how quickly an individual needs to accomplish the goal behind the locomotion. However, when experimenters asked participants to perform a walking task with their natural gait, participants slowed when anticipating slippery footing (Cham & Redfern, 2002). Clearly, motor behaviors are adaptable in different contexts (also see Loehr & Palmer, 2007).

The tools are in place within motor memory to reproduce time intervals. However, one problem with the theory is the covert calculations that a set of unspecified mental processes would need to compute time intervals. In the theory derived so far, the calculations would need to be far more complex than the accumulator's counting process.

We can eliminate the problem by reasoning that an explicit calculation of time does not need to be derived. Simply enacting or enacting and adjusting motor behavior drawn from motor memory will produce time intervals

directly. In the case of a rhythm, if an initial motor memory does not match the interval, then the motor behavior may be adjusted until it does.

### 1.3. Motor and physical realism

Another advantage of representing time with the use of motor memory is that the mind represents motor and physical realism. Parameters of physics in human motion are well represented in the mind. Consider Shepard and Metzler's (1971) classic research in mental rotation. They presented experimental participants with drawings of three-dimensional (3-D) geometric figures and asked the participants to indicate whether one figure was a rotation of another picture. The response time (RT) was proportional to the amount of rotation that was required to match the two figures when one manually rotated their 3-D equivalents.

The example above is only one illustration of motor realism. In another study (Kosslyn, Ball, & Reiser, 1978), participants memorized fictional maps and were asked various questions about the map (e.g., was the rock to the left or right of the tree?). Participants took a proportional amount of time to answer the question as it would take them to move their eyes from the spot on the map for the previous question to the spot on the map for answering the next question.

Decety, Jeannerod, and Prablanc (1989) extended these findings outside the realm of imagery for oculomotor or manual behavior. They found that when participants were asked to imagine walking or to actually walk to a target object, their estimated and actual duration were approximately equal. Based on this evidence and evidence like this, Jeannerod and Decety (1995) concluded that motor memory stores motor behavior with realistic parameters, including timing.

Guillot and Collet (2005) question the accuracy of duration estimates from mentally simulated movement. Their review finds that duration estimates are less accurate when one is estimating complex, singular (i.e., non-cyclical), or unskilled movements. Therefore the present theory of a motor–temporal link includes greater success of mentally simulated movement when those movements are simple, cyclical, and automatic.

The motor-realistic restraints on mental imagery create a system well suited to measuring time with motor behaviors. Motor behaviors may use mental imagery to constrain which motor memories represent an approximation of the interval. As shown by Brown and Bennett (2002), interval estimation improves when more examples of the interval occur in the environment. This can be explained by the continuous adjustments of motor parameters to approximate the rhythm (e.g., tapping to the beat of a musical selection, which conforms to Guillot and Collet's (2005) requirements for a simple, cyclical, and automatic type of movement to accurately represent time).

### 1.4. Long durations

Motor memory also provides a ready solution to the problem of estimating or producing longer intervals, which

is more error prone than estimating or producing short intervals but still possible (see Rakitin et al., 1998). Under the traditional conception of a mental timekeeper, the number of pulses necessary to estimate longer intervals grows larger and larger. The accumulator must therefore count an increasing number of pulses in an accurate way since most researchers attribute errors in timing to errors in the timing of pulse output from the timekeeper and to motor error when intervals are produced (e.g., Wing & Kristofferson, 1973). In the present theory, timekeeper error equates to error in the approximation of the initial motor memory while Wing and Kristofferson's (1973) claim is maintained that some error can be attributed to motor execution error.

Motor memories may also encompass sequences of motor behaviors (e.g., a walking gait is specified by multiple limb movements). Each step in the motor behavior sequence may segment a larger interval into smaller parts and so motor behaviors drawn from motor memory that involve multiple, repetitive motions represent a way to divide an interval into smaller parts. The accumulated errors for each of the steps in the motor sequence account for greater error with larger sequences.

### 1.5. Covert movement

Although we frequently observe people tapping or bobbing to music, interval estimation does not always produce observable movement. Inner speech (e.g., Cassenti & Reifers, 2005) is one method of using the cognitive motor system to generate duration even in the absence of overt, observable motion. In speech, words take a certain amount of time to produce (Baddeley, Thomson, & Buchanan, 1975) and so the motor behaviors for vocalization can be used to measure time intervals.

Participants in timing studies may not show overt motor behaviors (e.g., speech), but Baddeley et al. (1975) found that the length of time to produce a word in inner speech is proportional to the time it takes to say the word aloud. In another study, Ellis and Hennelly (1980) found that Welsh speakers took much longer to compute math problems than English speakers. Ellis and Hennelly (1980) reasoned that Welsh speakers used number words with more syllables than those in the English language. They concluded that Welsh speakers took longer to compute math problems because they took time to sound the words in inner speech. The study shows that inner speech represents motor realism, and therefore, inner speech can be used as a covert method of reproducing time intervals.

### 1.6. Summary

Cognitive motor processes use motion parameters and weight and height restrictions on bodily effectors to offer approximations of environmental intervals. The physical and motor realism restrictions in mental imagery offer an opportunity to approximate intervals through stored motor memories, and enacting these motor behaviors helps the system adjust to errors in interval estimation. A motor–temporal link also allows attribution of errors to specific causes without assuming perfect accumulator

calculations. Motor behaviors are built to segment intervals, and speech or inner speech can be used to measure time intervals, not just traditional bodily effectors such as arms and legs. Killeen and Weiss (1987) discuss this segmentation strategy to interval timing and reason that it benefits temporal cognition by reducing the amount of variability between estimated and actual durations by breaking larger durations into smaller durations that are more readily estimated.

## 2. Psychological evidence for the motor–temporal link

Experiments in temporal cognition often involve producing time intervals through tapping (e.g., Benuzzi, Basso, & Nichelli, 2005; Brown, Newcomb, & Kahrl, 1995; Fortin & Breton, 1995). Participants produce a response for each anticipated or measured beat, thereby allowing researchers to gauge how well participants approximate an interval. Wing and Kristofferson (1973) used this technique to measure error in temporal production. However, according to the motor–temporal link theory proposed here, the chance to tap and thereby control the parameters of their motion may have aided participants in producing the correct rhythm.

### 2.1. Motor timing strategies

Jones and Boltz (1989) claim that tapping or any other motor movement is an aid to interval estimation. Evidence can be seen whenever a musician taps or moves another bodily effector in a repetitive motion. Jones and Boltz (1989) assert that tapping is a way of aiding a timekeeper and accumulator system in measuring intervals. However, given the claims made above, it may be that the tapping itself keeps the musicians on beat with the music by indicating the timing of each note in the musical selection.

Speech and inner speech are also used in the same way. Gilliland and Martin (1940) coined the term *chronometric counting* to describe a strategy for measuring time intervals by counting. A typical scenario involving this is children who play a game such as hide-and-go-seek in which a seeker must give everyone about the same amount of time to hide before seeking. The seeker will count “one Mississippi, two Mississippi...” to give hiders the same amount of time to hide every round. Hinton and Rao (2004) found that participants who used a verbalized counting strategy such as this showed improved time estimation over those who were not allowed to count.

Cassenti and Reifers (2005) implemented this type of strategy into ACT-R (Adaptive Control of Thought – Rational; Anderson & Lebiere, 1998), a major cognitive modeling system, with a model of a counting task in which participants counted asterisks that appeared on a computer screen one at a time (Carlson & Cassenti, 2004, Experiment 2). The asterisks appeared with a rhythmic pace or an irregular pace (i.e., a pace with a range of values but averaging the rhythmic pace). If the pace was rhythmic, participants showed fewer errors but a tendency to undercount. If the pace was irregular, participants showed more errors and a tendency to overcount.

Cassenti and Reifers (2005) reasoned that the undercounts were equally likely in both conditions and could be attributed to a system-wide process in human cognition and in ACT-R (i.e., activation of a previous number memory instead of a new number). They attributed the overcounts to the inner speech strategy outlined in the previous section. When participants count rhythmically, they can use the length of time to speak the number of the current item to predict when the next item will appear and time their count to coincide with that event. This interval can be the same for every count if the participants abbreviate some numbers (e.g., “seventy-seven” to the two syllable “sev-sev”) or extend some numbers (e.g., “two” to the two syllable “ta-oo”) to make them the same syllable length. In an irregular interval schedule, the participants can still use the inner speech strategy, but they must tune the speech to the minimum time in the range or risk losing track of the sequence (i.e., if the asterisk appears at the minimum time and the participant is not yet ready to count it). In the intervening time between the minimal speaking time and the time that the item usually appears, participants risk counting one item twice (i.e., the representation in verbal working memory triggers the count and the appearance of the asterisk triggers another). Cassenti and Reifers' (2005) ACT-R model represented the data with a high degree of reliability.

The Cassenti and Reifers (2005) model is just one behavioral account of how the participants in the Carlson and Cassenti (2004) studies kept track of time. Carlson and Cassenti observed (though did not report among their findings) that participants tended to move in steady beat with the appearance of asterisks in the rhythmic condition (e.g., foot tapping or head bobbing). They concluded that the participants were using repeated motor behaviors for the same reason that musicians tap rhythmically – to use motor behavior to keep track of time.

Killeen and Fetterman (1988) hypothesized a similar mechanism within the field of animal behavior. When test animals were put into a time-sensitive reinforcement schedule, they used their reinforced behaviors to accommodate the interval schedule. For example, Killeen and Fetterman (1988) cited a study by Killeen, Hanson, and Osborne (1978) in which pigeons pecked a key and had to approximate a 30-, 100-, or 300-s interval. The pigeons used the pecking behavior to adjust the mean and standard deviation of the pecks to ensure that the final reinforced peck occurred at the correct time by increasing or decreasing the frequency of pecks, speed of pecking, or both. The Killeen and Fetterman (1988) work reinforces not only that motor behavior plausibly controls timing, but also that the motor–temporal link theory applies to animals in addition to humans.

### 2.2. Challenges to a motor–temporal link theory

Despite all the psychological and everyday evidence for motor control of temporal cognition, the traditional time-keeping theories maintain their status as the preferred models of temporal cognitive researchers, including the preference of Jones and Boltz's (1989) theory of entrainment and Killeen and Fetterman's (1988) behavioral theory

of timing. The motor–temporal link theory proposed here faces obstacles to becoming a competitor of the traditional theories of temporal cognition. First, providing empirical support for the use of motor behaviors is difficult. One can observe motor behaviors during time estimation, but quantifying the motor behaviors within an experiment is nearly impossible. Training a camera on a participant may not necessarily provide the evidence needed since motor behavior can be performed covertly (e.g., tiny movements or using a non-visible appendage such as the tongue). In addition, a camera will not detect inner speech.

The second difficulty in empirically supporting the theory is that temporal production (i.e., producing intervals with motor behavior) is one of the primary tools for studying temporal cognition. If the motor behavior is incorporated into the experimental instructions, then a researcher can make no claims as to whether the participant would produce the motor behaviors to aid temporal cognition, rather than because it was a requirement of the study. In addition, instructing some participants to tap and some to refrain from tapping will not add confirmatory evidence to the hypothesized motor–temporal link if participants in the latter group can use motor behavior covertly.

The importance of Hinton and Rao's (2004) findings take on greater importance due to these limitations. The finding that participants who are permitted to use a speaking strategy during a temporal cognitive task perform better than those who must be silent demonstrates that motor behavior helps performance adds critical evidence to the motor–temporal link theory.

More experimental evidence would aid the motor–temporal link theory. In the next section, I turn to neuroimaging evidence for the motor–temporal link.

### 3. Neuropsychological evidence for a motor–temporal link

If motor behavior is used to measure time intervals, then there should be evidence of activation of motor areas of the brain during temporal cognitive tasks. Below is an outline of a subset of this evidence.

#### 3.1. Basal ganglia and cerebellum

Gibbon, Malapani, Dale, and Gallistel (1997) reviewed evidence for brain area activation during temporal cognitive tasks. They focused on two areas of the brain that were most characteristic of temporal cognition: the basal ganglia and the cerebellum. Both the cerebellum and the basal ganglia are well known for motor function (see Carlson, 1995 for a review).

Matell and Meck (2000) cited evidence for activation of the basal ganglia and cerebellum during a timing task and generated a neuropsychological model of the relation between brain regions and temporal cognition. Based on this model, they concluded that among the functions of the basal ganglia are timekeeping and motor functions with no explicit connection between the two functions. From the standpoint of a motor–temporal link, however, the motor

behavior produced from the basal ganglia may measure time, and therefore, the two functions are not independent.

Meck (2006) found that lesions in different areas of the basal ganglia in a time-based reinforcement schedule differentially affected a mouse's timing of a behavior or the motor behavior itself. The motor–temporal link theory also supports two different sets of processes in behavior production that is used to reproduce duration. One set encompasses processes that apply velocity and distance requirements to the behavior and another produces the behavior. These may be differentially affected by different lesions as Meck (2006) showed.

Meck's (2006) results may equally support the traditional accounts of an internal timekeeper. The interpretation presented here is one of many possible explanations and reinforces the goal of presenting the motor–temporal link theory as a reasonable competitor to traditional accounts rather than as a replacement of them.

#### 3.2. Pre-frontal cortex and cerebellum

Mangels, Ivry, and Shimizu (1998) focused on the relation between the cerebellum, pre-frontal cortex, and temporal cognition. The pre-frontal cortex is generally believed to be the part of the brain that processes higher-level cognition, emotion, and motivation. These functions include monitoring execution of motor behavior for errors, including sequencing and timing (de Jong, Willemsen, & Paans, 1999).

The Mangels et al. (1998) study showed different functions for the cerebellum and the pre-frontal cortex in temporal cognition. For short durations, the cerebellum was active while the pre-frontal cortex remained relatively inactive. For longer durations, both regions were active. The theory outlined here suggests that shorter durations require little complexity since the motor system can represent a small duration by simple motor behavior (see Guillot & Collet, 2005). The larger durations require longer sequences of behaviors because more behaviors must be conjoined to approximate larger durations. Mangels et al. (1998) came to the same type of conclusion while also accepting a Matell and Meck (2000) type of conclusion in which they claim that the cerebellum has separable motor and timing functions.

Within the pre-frontal cortex is a brain region called the Supplementary Motor Area (SMA), which is involved in motor sequences. Findings from Rao, Mayer, and Harrington (2001), Halsband, Ito, Tanji, and Freund (1993), and Macar, Coull, and Vidal (2006) indicate activation of the SMA during temporal control. Lesions of the SMA have been linked to an inability to perform movements in novel tasks that required precise sequences of motion (Ackermann, Daum, Schugens, & Grodd, 1992). Disruptions of complex motor patterns in temporal cognition can be traced to lesions of the SMA with the findings of Macar et al. (2006), Mangels et al. (1998), and Rao et al. (2001). Therefore, in addition to the cerebellum and basal ganglia representing both temporal and motor function, the SMA also represents both. A more likely explanation to separate functions of both is a reliance of temporal cognition on motor function.

A final source of evidence from neuropsychological studies is from Parkinson's disease. Parkinson's disease is known to affect both motor behavior and temporal cognition (e.g., Meck, 1996). Meck (1996) attributes both cognitive deficits to disturbances in the basal ganglia, which he suggests controls both temporal cognition and motor behavior which are themselves distinct functions. However, according to the motor–temporal link theory, evidence from Parkinson's disease adds further support to the theory that motor behavior is used to measure time intervals.

Given the evidence from neuroimaging studies (as well as other research evidence from neurocognitive studies) a motor–temporal link appears to be a promising alternative to the internal timekeeper-accumulator models. If the internal timekeepers include mechanisms such as clocks, oscillators, and accumulators, then one would assume that these mechanisms reside in specific brain structures. It is unlikely that all brain imaging studies would find temporal cognitive functions only in areas previously associated with motor control.

#### 4. Implications of motor–temporal link

An important function of temporal cognition in everyday life is in multi-tasking. When an individual has to perform multiple tasks at the same time, he or she must devote time to steps in each of the tasks, especially if the tasks are under deadlines or time pressure. The situation becomes more complicated, considering the findings of Brown (1997, 1998) that temporal cognition itself requires attentional resources. Since multi-tasking is an attention-demanding situation (e.g., Baddeley & Hitch, 1974), an individual employing temporal cognition will show decreased performance as attention divides across tasks. Brown and Bennett (2002) found that resource demands decrease as people gain more temporal skill (i.e., an ability to accurately produce or measure time intervals). Understanding the mechanisms of temporal cognition may aid researchers in deriving methods of improving temporal skill.

Multi-tasking is particularly intense inside a tactical operations center (TOC) (see Glenn, Medby, Gerwehr, Gellert, & O'Donnell, 2003) during battle conditions where military personnel must make just-in-time decisions while performing other tasks. Using temporal cognition while multi-tasking under the stress of life and death circumstance would make a TOC operator's duty much more difficult. Learning temporal skill would lessen the burden of workload and improve human performance inside a TOC.

Another consideration is that decreases in performance with divided attention are magnified when an individual suffers from an attention deficit disorder (ADD). With a propensity to become distracted, an individual with ADD will have difficulty doing any task while engaging temporal cognitive processes. In addition, individuals with ADD suffer from motor control problems (Kadesjo & Gillberg, 1998), and the severity of their attentional problems predicts the level of difficulty with motor coordination (Piek, Pitcher, & Hay, 1999).

#### 4.1. The interactive metronome and conductors

One proposed method of improving the behavior and performance of individuals with ADD is to focus on their timing and rhythm skills by improving their ability to measure intervals. The **Interactive Metronome® (IM, U.S. Patent No. 7,122,004, 2006)** offers a method of improving temporal skill in line with the motor–temporal link theory. The IM is a device that provides a beat through headphones and tracks a participant's ability to match that beat. Through constant feedback in the beat patterns from the headphones, the IM can improve motor timing and motor control (Stemmer, 1996). Shaffer et al. (2001) found that IM intervention with children who have ADD and hyperactivity (ADHD) showed subsequent improvements in academic performance over groups that did not receive treatment or received a different treatment. While several mechanisms may explain these findings, one explanation is that increased skill in one task during multi-tasking will improve overall performance (Hirst, Spelke, Reaves, Caharack, & Neisser, 1980).

The Shaffer et al. (2001) study demonstrates that children who suffer from attention and motor problems improve in a variety of academic tasks that are not generally related to temporal cognitive skill (e.g., concept discrimination). The results show that improving the timing of movement increases performance in seemingly unrelated tasks.

These findings are important to the motor–temporal link theory because they add evidence that it is not just temporal improvement but temporal improvement through the use of a device that more directly improves motor coordination. Specifically, the device may allow the participant to link certain types of movement with certain intervals. If these movement–timing pairs are reinforced in memory, then the participants can rely on recall to retrieve the proper motor memory instead of relying on attentional resources to select a motor memory with approximate timing (for a similar account of addition skill, see Lebiere, 1999).

Teamwork and cooperation are an increasingly important concept in psychological research today. Just as the IM may aid individual timing skill, Allender, Cassenti, and de Pontbriand (2005) suggest that in a group task, one member of the group be designated as a conductor (analogous to the conductor in front of a symphony). This would give other members of the group an opportunity to correct motor behavior without using attentional resources of their own to form motor images.

The strategies for improving temporal cognition with the IM or with a conductor are most important in military tasks. When life is in the balance during military actions, Soldiers, Marines, and other military personnel must rely on good motor coordination and timing skills with individual and group actions. For example, room clearing is an important operation in hostage situations where taking the enemy by surprise and coordinating the entry of many Soldiers at once through a doorway are important elements. If the team coordinates movement well, then all team members can work at a consistent pace and act as one unit. Allowing the military to acquire and develop temporal

skills through training, equipment, or strategies may make a large difference in dire situations such as room clearing and performing operations in a TOC as discussed above.

## 5. Summary of the case for motor–temporal link theory



Establishing the motor–temporal link model as a competitor to the traditional model of internal timekeeper and accumulator requires a strong case because of how engrained the traditional model has been in temporal cognitive research. The first argument in favor of motor–temporal link theory rests on empirical evidence and the state rests on how the new theory simplifies the current state of temporal cognitive theories (thus satisfying Occam's Razor, a core scientific principle).

The first line of evidence is psychological. Psychological evidence indicates a place for motor function in measuring time intervals (e.g., Shaffer, 1982). This can be observed with tapping musicians (e.g., Jones & Boltz, 1989) and using speech to segment long intervals (e.g., Hinton & Rao, 2004). Mangels et al. (1998) found evidence of the segmentation strategy in their neurological findings as discussed above. The problem with directly observing the motor–temporal link is also shared by the traditional model's internal timekeeping system that has no directly observable behavioral repercussions. This evidence supports the superiority of motor–temporal link theory, which explains and incorporates motor behavior during temporal cognition.

Next, motor–temporal link theory may be an improved explanation of temporal neurocognitive evidence. Instead of two distinct functions coinciding in the same areas of the brain (even between motor responses when the motor system should not otherwise be engaged), one function (i.e., temporal cognitive function) may be the result of the other (i.e., cognitive motor function, which includes two components – applying motion parameters to a behavior and producing the behavior). Also, a disease such as Parkinson's has both motor and temporal cognitive repercussions, which is difficult to explain by a traditional accumulator account of temporal cognition.



Finally, the evidence of improvement in temporal cognition through the use of motor behavior with the IM favors the motor–temporal link theory. The traditional model includes a covert accumulator that should have no benefit from improving skills in motor behavior.

The motor–temporal link theory also allows a reduction in complicated schemas for how temporal cognition works. First, the pulse-emission processes (i.e., oscillators or clock mechanism), accumulator, and covert counting mechanisms would be removed from the process. That would neutralize the debate over whether the timekeeper is an internal clock (Church & Broadbent, 1990) or multiple oscillators with different frequencies (Gibbon et al., 1984). The motor–temporal link theory also reduces the amount of conjecture as to how evidence fits with the traditional account, including explanation of distinct processes for motor and temporal function in the same brain regions.

Second, the division between motor timing research (e.g., Rosenbaum, 2002) and temporal cognitive research

could be removed. If cognitive motor skills have the ability to specify movement parameters (e.g., Gielen et al., 1985), then each motor memory has a unique time interval with two sources of variability: the difference between a chosen motor memory and the environmental interval (i.e., the timekeeper variability in Wing & Kristofferson, 1973) and the variability in producing the interval (i.e., the second source of variability in Wing & Kristofferson, 1973). Under motor–temporal link theory, motor timing is the tool used to estimate or produce time intervals.

The motor–temporal link theory rests on existing cognitive capabilities, including recalling motor memories, executing them, and adjusting them to fit to the parameters of the current situation. Given that these cognitive and motor skills exist in animals, there is also reason to believe that animals may possess the same motor–temporal link (see Killeen & Fetterman, 1988 for evidence). As such, the theory does not rest on hypothesized functions such as an accumulator or distinctive functions that show activation in the same regions of the brain.

Mounting psychological and neuropsychological evidence supports the new motor timing link theory. The present theory, in which timing is intricately related to motor performance and motor patterns, may provide both another explanation for the reported successes of devices such as the IM. It also gives credence to investigations into strategies that could improve both physical and cognitive performance of military tasks, in which success is crucial to survivability.

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