Analyzing variable behavioral contingencies: Are certain complex skills homologous with locomotion?

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ABSTRACT

This paper considers behavioral contingencies that change as a function of time, of the individual's own behavior (as in locomotion and reading), of the behavior of other parties or of interactions with them. A detailed analysis of locomotion and of reading out loud shows that the behavioral contingencies for these are virtually the same. The terrain being traversed and the locomotion behavior involved are shown to be analogous to a segment of text being read and the articulation of the words. In both cases, successive upcoming segments are perceived and processed, and during the processing phases, motor behavior is formulated. In both, the smooth concatenation of the motor phases for successive segments requires buffering. Both involve corrective or digressive actions in response to obstacles or unanticipated stimuli encountered. Both involve looking ahead at the upcoming segment and processing it while the motor phase of the prior segment is still in progress. For both, the size, entropy, familiarity, and other attributes of the upcoming segment are parameters of the performance. It is suggested that locomotion has similar parallels with certain other complex skills, such as listening, copying, receiving Morse code, simultaneous interpreting, and certain types of performance, and may therefore be their phylogenetic prototype and biological homologue.

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1. Static and variable contingencies

Behavioral contingencies fall into two broad categories: those involving a single individual and those involving multiple individuals. Each of these categories can in turn be subdivided into static and variable contingencies. Variable contingencies may change as a function of time, external events, or ongoing behavioral processes. Research in motor performance learning, behavioral economics, sociology, and neuroscience has often involved variable contingencies and multiple subjects.

Some of the simplest variable contingencies are those that change as a function of time. For example, the valence of a consequence can become increasingly negative, as when one delays having a dental or medical problem attended to or a tax penalty taken care of, or increasingly positive, as when a farmer waits for a harvest to be ready or any situation in which "time is on your side" (Mechner, 2008a, p. 132). In some of these the valence of the consequence passes through a maximum, as when fruit ripens or a roast bakes in the oven. In such contingencies the valence of the prevailing circumstance, prior to the occurrence of the sub-

sequent one, may also change as a function of time, as when the individual becomes hungrier or thirstier or perceives an approaching threat. Such contingencies may or may not include an external time marker, like a clock.

2. Complex variable contingencies

Variable contingencies that change as a function of the subject's own behavior are more complex. An important instance of these is the one that governs locomotion, a primordial behavioral capability already present in many one-celled organisms. Locomotion is the underlying functionality for foraging, predation, pursuit, and evasion (Kotler et al., 1994; McElroy et al., 2008; Woollacott and Jensen, 1996).

The present paper attempts to show how a detailed behavioral contingency analysis of locomotion reveals that it has many nontrivial structural parallels with certain other complex behaviors like reading, listening, copying, simultaneous translation, certain aspects of performance, and various interactive behaviors. The idea that these behavioral capabilities are related is not entirely new (e.g., Ericsson and Charness, 1994). But their structural parallels with locomotion suggest that locomotion may be their phylogenetic prototype or evolutionary ancestor, and thus biologically (though

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not functionally Love, 2007) homologous[1] with them (Mechner, 1995, pp. 73–82). By providing the neural scaffolding of other complex capabilities (possible behavioral homologues), locomotion may well have played an important role in the evolution of our neural architecture.

One value of this type of analysis is that identification of behavioral homology and functional parallels can provide guidance to neuroscience research. A prominent example of this is the strategy that led Eric Kandel to search for the neural mechanisms of human learning and memory by studying primitive models of Pavlovian learning and memory in the sea snail Aplysia (Kandel, 2006). Also, the exploration of behavioral and associated neurological homologues in different species (e.g., studies of the mirror systems and language-related brain areas) is currently a vibrant field of neuroscience research (Fabbri-Destro and Rizzolatti, 2008; Gannon et al., 1998).

3. Characteristics of locomotion

A prerequisite for a useful behavioral contingency analysis of locomotion is a detailed understanding and description of the behavior involved—one that specifies the features of locomotion that a behavioral contingency analysis must address.

Virtually all locomotion requires (a) perceiving the upcoming terrain (through visual, auditory, chemical, or tactile means, depending on environment and species, e.g., bats use radar, some marine animals use sonar or chemical perception, and many insects use olfaction) and processing the perception, culminating in the formulation of the locomotion movements; (b) executing the locomotion movements; and (c) making adjustments in response to possible feedback during terrain traversal when and if unanticipated terrain features or other diverting stimuli are encountered (Lee and Lishman, 1977; Montello, 2005; Pearson, 1993).

This *a–b–c* sequence keeps recycling as the animal moves through the environment. The perception and processing phase (henceforth referred to as the "pp phase") may involve looking, discriminating and conceptualizing the features of the perceived terrain, and formulating locomotion movements or other motor behavior appropriate for those features (henceforth referred to as the "motor phase"). For example, a runner running at a speed of, say, 6 miles/h over uneven terrain might, at any moment, be perceiving the stretch of terrain 10–20 ft ahead, and would plan the appropriate footwork for that stretch during the 1 or 2 s it would take to reach the beginning of that stretch. While then traversing that stretch, the runner would already be bringing the next stretch into view and might begin to formulate the motor routines appropriate for it.

4. Virtual terrains

While traversing a stretch of terrain, the animal will often encounter unpredicted terrain features that function as discriminative stimuli (e.g., obstacles or details of the terrain) that were not perceived or predicted before they were reached. Such feedback may result in corrective adjustments and revisions of the planned locomotion movements or, depending on the stimuli, in side excursions or other digressions. This can happen multiple times during traversal of a stretch, as each substretch becomes perceptible. The contingency structure of such revisions and digressions has the

same *a–b–c* structure as the overall contingency and these can therefore be viewed as reiterations of that structure, which can, in turn, have further nested reiterations, forming a recursive regress.

For example, in foraging, stimuli that come into view during locomotion might be mushroom patches or berry bushes. The pp phase of such a second order terrain might include visual scanning and conceptualization of that terrain's features (e.g., number, types, accessibility of the berries, etc.) and planning a possible action program (a detour to the berry patch, picking certain ones, etc.). This activity would be analogous to the planning of corrective steps and body movements in the pp phase of basic locomotion. In pursuit or escape, second order terrains may involve visual and auditory stimuli generated by the pursued or pursuer, and the pp phases would again include the formulation of appropriate adjustments of actions.

5. The staggered phases

Smooth locomotion demands that every set of overt locomotion movements start at exactly the moment the previous one ends. If too soon, the required effectors would still be engaged in executing the previous cycle's locomotion movements, resulting in interference, like tripping. If too late, a time gap would occur between successive sets of motor phases.

Since each cycle's pp phase must be completed before the formulated motor phase for the next cycle can start, successive cycles must overlap, in staggered fashion, offset by the average duration of the motor phase, as shown in the idealized diagram below.
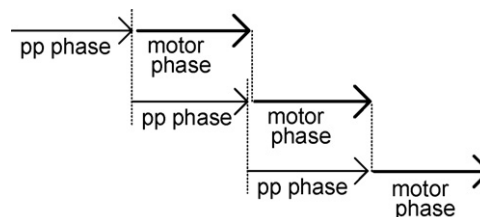

6. Uneven terrain: varying lengths of phases

The above diagram makes the simplifying assumptions that each pp phase begins exactly when the previous one ends, that only one pp phase can be in progress at a given time, and that all phases are of exactly equal length. But real terrains are normally uneven, in an unpredictable way, and the length of the *a–b–c* cycle will therefore vary just as unpredictably.

The following diagram shows how, if the pp phase of the next cycle is too short, the formulated motor behavior would be ready to be initiated too soon, that is, while the previous cycle's motor phase is still in progress, with resulting interference.
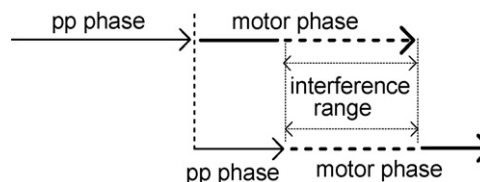
If a pp phase is too long, however, a gap would occur after completion of the previous cycle's motor phase:
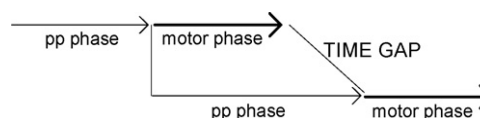
Note that the same types of problems would result from variations in the durations of the motor phases.

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[1] The concept of homology in modern genetics and evolutionary psychology is not without controversy (Wagner, 1989). Biological homology is defined by Fitch (2000) as "the relationship of two characters that have descended, usually with divergence, from a common ancestral character... Characters can be any genic, structural or behavioral feature of an organism."

7. The buffering period

This type of problem is solved, throughout biology, by means of buffering (Grossberg, 1980). In the case of locomotion, such buffering is achieved by the short-term retention in memory of the programs for the motor phase formulated in the pp phase. The insertion of such a buffer after the pp phase in cycle n permits a longer pp phase to occur in cycle $n+1$ without delaying the start of cycle $n+1$'s motor phase beyond the end of cycle n's motor phase.
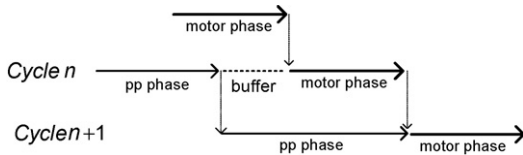
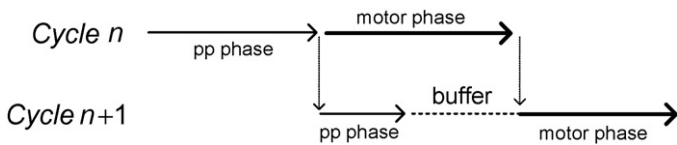If a pp phase is too short, on the other hand, a buffering period after the short pp phase would permit the motor phase in cycle $n+1$ to be delayed until the end of the preceding one (in cycle n), thus preventing interference with it.


Such buffering periods would accommodate the expected variations in the durations of the a–b–c cycles due to terrain variations, and thereby permit each successive motor phase to start at the moment the previous one ends.

8. The length of buffering periods

In the previous diagram the buffering period is of exactly the right length for the motor phase of cycle $n+1$ to start at the exact moment the motor phase of cycle n terminates. So why cannot all buffering periods be long enough to accommodate even the longest conceivable pp phase? Because the buffering phases of successive cycles would then sometimes overlap, possibly overloading the available memory storage and retention capacity for such buffering:
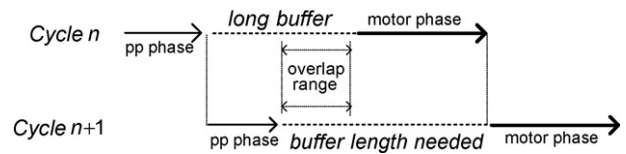

This optimal length depends not only on memory capacity but also on the speed of locomotion, the perceptibility of the upcoming terrain, the processing speed, and the time that elapses between completing the pp phase and physically reaching the stretch of terrain for which the movements were formulated. When the variability of all of these factors is too great for buffering to create perfect alignment of the motor phases, locomotion pauses would still need to occur.

9. A behavioral contingency analysis[2] of locomotion and reading out loud

The next diagram shows the general behavioral contingency analysis of both locomotion and reading out loud. It shows that the same diagram reflects and accommodates all of the complex interrelationships described and discussed above, as well as some others that they have in common. The legend in the table below, which shows two separate columns for "locomotion" and "reading out loud," defines and explains all of the symbols that appear in the diagram. It makes the point that reading out loud has a behavioral contingency structure that is very similar to that of locomotion.

The As in the diagram represent acts defined by their subscripts, and the ts in the upper right of some of the As refer to the act's duration. The Cs represent the circumstances or situations in which the acts can occur, and the attributes M, E, F, or p of these Cs are defined in the table. Terms listed vertically (in arbitrary order) inside a bracket are assumed to be in effect at the same time.
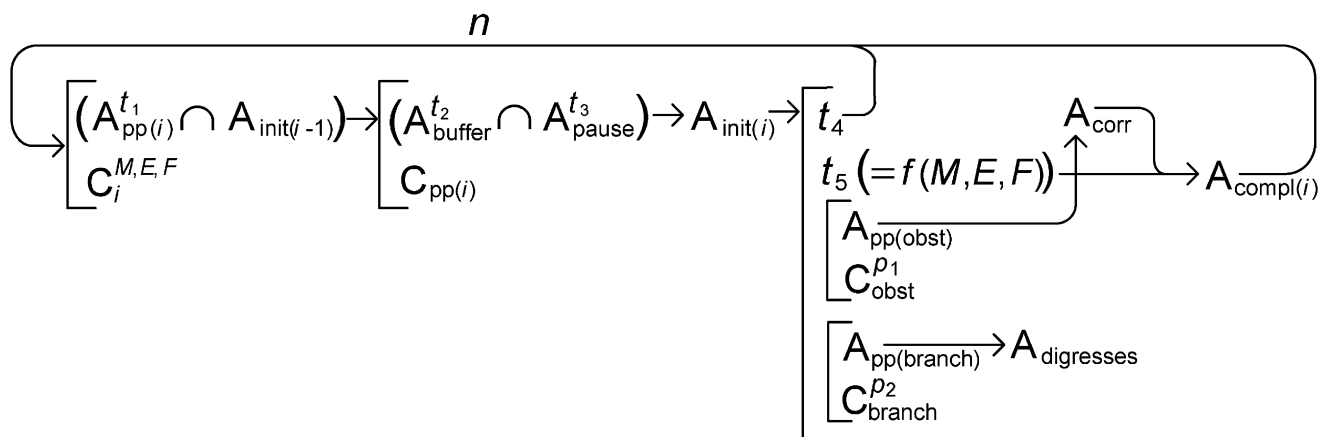
[2] The formal language for the analysis of behavioral contingencies used here is described more fully in Mechner (2008a,b).

Legend:

Diagram feature	Locomotion	Reading out loud
i—the ith segment, which is assumed to be incremented after each recycling.	The ith segment or stretch of the terrain being traversed, assumed to be incremented after each recycling.	The ith segment of the text being read, which is assumed to be incremented after each recycling.
n—the nth recycling, which is zero during the first segment.	The nth recycling to the next segment of terrain, which is zero during traversal of the first segment of terrain.	The nth recycling to the next segment of text, which is zero during reading of the first segment of text.
$C^{(M, E, F)}_{(i)}$—perceived segment (i) having attributes M, E, and F.	Perceived stretch or segment (i) of current terrain, having attributes M, E, and F.	Perceived segment (i) of current text, having attributes M, E, and F.
M—the magnitude or length of the perceived segment, which depends on E and F.	Distance that can productively be looked ahead along the stretch of terrain, which depends on E and F.	Distance that can productively be looked ahead at the segment of text, which depends on E and F.
E—the entropy (information content) of the perceived segment. See explanation in the text below.	The regularity, recognizability, familiarity, or perceptibility of the stretch of terrain.	The recognizability, familiarity, perceptibility, degree of organization, or verbal coherence of the text.
F—special physical features and attributes of the segment.	Slope of the terrain, wind, temperature, characteristics of the medium (nature of the ground, air, water, or light).	Font size and style, contrast of typeface, illumination, ambient noise, physical distractions.
$A_{pp(i)}$—perception and processing of segment (i), and formulating the motor program for it.	Seeing or sensing features of (i), processing these, and planning the locomotion movements for stretch (i).	Seeing text segment (i), reading it, and planning the articulation of the words of segment (i).
$A_{init(i-1)}$—initiation of the motor phase of the preceding segment.	Initiation of strides or other motor behavior involved in traversing stretch $(i-1)$.	Initiation of articulation or vocalization of the words of text segment $(i-1)$.
$A_{init(i)}$—initiation of the motor phase of segment (i).	Initiation of strides or other motor behavior involved in traversing stretch (i).	Initiation of articulation or vocalization of the words of text segment (i).
t_1—time consumed by $A_{pp(i)}$	Processing time of (i) which depends on M, E, and F.	Processing time of (i) which depends on M, E, and F.
$C_{pp(i)}$—consequence of completing the pp phase for segment (i), including the formulation of the motor behavior.	Consequence of completing the pp phase for terrain segment (i), including formulation of the motor behavior for locomotion.	Consequence of completing the pp phase for text segment (i), including formulation of the motor program for articulation of the words.
A_{buff}—retention of the action plan for segment (i) until segment $(i-1)$ is completed.	Retention of the plan for the locomotion movements for terrain segment (i) until segment $(i-1)$ is completed.	Retention of the plan for the articulation of the words for the text segment (i) until segment $(i-1)$ is completed.
$A_{pause(i)}$—a possible pause prior to $A_{init(i)}$ for any purpose, including rest or supplemental buffering.	A possible locomotion pause prior to $A_{init(i)}$ for rest, lingering, survey of the environment, or other interpolated activity.	A possible reading pause prior to $A_{init(i)}$ for rest, consideration of the meaning of the text, or other interpolated activity.
t_2—length of time the motor plan for segment (i) is retained in buffer pending completion of segment $(i-1)$.	Time for which the plan for the locomotion movements for terrain segment (i) is retained in buffer pending completion of segment $(i-1)$.	Time for which the plan for the articulation of the words for the text segment (i) is retained in buffer pending completion of segment $(i-1)$.
t_3—time consumed by $A_{pause(i)}$, which can function as an additional buffer pending completion of segment $(i-1)$.	Time consumed by a possible locomotion pause prior to $A_{init(i)}$ for rest, lingering, survey of the environment, or other interpolated activity.	Time consumed by a possible reading pause prior to $A_{init(i)}$ for rest, consideration of the meaning of the text, or other interpolated activity.
t_4—time between $A_{init(i)}$ and initiation of the nth recycling. Recycling can occur while segment (i) is still being executed.	Time between $A_{init(i)}$ and initiation of the nth recycling, which can occur while terrain segment (i) is still being traversed.	Time between $A_{init(i)}$ and initiation of the nth recycling, which can occur while text segment (i) is still being read.
t_5—time consumed in execution of segment (i).	Time consumed in traversing terrain segment (i).	Time consumed in reading and articulating the words of text segment (i).
$A_{compl(i)}$—completion of segment (i).	Completion of traversing terrain segment (i).	Completion of reading and articulating the words of text segment (i).
$C^{p1}_{obstacle}$—an obstacle, with probability p_1 of occurring, that interferes with the planned motor behavior for segment (i).	Possible terrain features not previously perceived or anticipated that block or impede the planned motor behavior.	Possible letters or words that cannot be read, recognized, or pronounced, or other possible obstacles to reading.
$A_{pp(obst)}$—perception and processing of the obstacle, interrupting t_5 (vertical arrow cutting the horizontal arrow) and enabling possible A_{corr}.	Perception and processing of such terrain features and planning corrective acts, interrupting the process of traversing the terrain stretch.	Perception and processing of letters or words that cannot be read or pronounced and planning ways to respond to these, interrupting the reading of the text segment.

Diagram feature	Locomotion	Reading out loud
A_{corr}—executing corrective acts required for $A_{compl(i)}$ to occur.	Corrective acts or taking an alternative path around the obstacle.	Trying to decode the word or skipping it, or overcoming the obstacle.
C^{p2}_{branch}—any diverting stimulus (with probability p_2) that could result in deviation or digression from the plan (other than an obstacle).	A possible better path to take, or a possible unpredicted and previously unperceived reinforcement opportunity or threat.	Possible text content or meaning that might prompt thought, comment, or some other unanticipated deviation from continuous reading.
$A_{pp(branch)}$—Perception and processing of deviations from the planned behavior, and planning appropriate actions.	Perception and processing of a better path to take, of an unpredicted reinforcement opportunity, or of a need to avoid or escape, and formulation of appropriate actions.	Perception and processing of text content, meaning, and/or formation of a concept, and formulation of a comment or of some other deviation from the read text.
$A_{digresses}$—deviating from the planned actions for segment (i) in response to possible C^{p2}_{branch}. (Note: The interruption of t_5 by $A_{digresses}$ is not shown.)	Taking a better path or evasive action, pursuing an encountered opportunity, or digressing from the planned path for any reason.	Initiating a "train of thought," idea, comment, or other behavior that may interrupt or proceed concurrently with reading.

Note: For the first stretch of terrain traversed (or first segment of text read), n is zero, as there have not yet been any prior recyclings, while $A_{pp(i)}$ refers to the first segment.

In the case of locomotion, the beginning of terrain stretch (i) would first have to be reached physically and thus be at least partially perceptible before processing that stretch can begin, which also depends on the immediately prior segment ($i−1$), if there was one, having been at least initiated. In the case of reading, the eye would have had to move to the next segment of text. That is why $A_{pp(i)}$ and $A_{init(i−1)}$ are connected with the ∩ logical "and" symbol. The time t_5 it takes to complete each segment and the time t_1 required for completion of each pp phase both depend on the segment's magnitude M (length), its entropy E (which is a function of its organizational features and the individual's history with respect to the segment), and its other attributes F. The combined times t_2 for the buffer period and t_3 for the "rest" period (these also being connected with the ∩ symbol), can provide time (if needed) for the preceding segment to go to completion before segment (i) is initiated. The time period that must elapse before each successive next cycle can begin, so as to achieve the required staggering of cycles, is an automatic consequence of these contingencies and therefore does not require separate notation.

10. Length of the perceived segment and its entropy

One of the characteristics shared by locomotion, reading, and related skills is that information regarding upcoming and preceding segments is useful in cueing the next acts. There are two aspects to this. One is that the farther ahead the individual can "see," that is to say, the more upcoming information is perceived at one time (and the more past information is remembered), the fuller will be the conceptualization and interpretation of the immediate segment, with corresponding effects on the overt motor behavior.

In locomotion, for instance, looking only one stride ahead would not provide the terrain cues for selecting and programming the most efficient paths over uneven terrain, and the runner would have to run slowly enough to avoid all possible obstacles. The farther ahead the runner looks, the more efficient the paths he can select and program and the faster he can run. Analogously, in reading out loud, if the reader looks only at the word he is about to read, he will read slowly and haltingly and without the linguistic rhythms, cadences, and inflections that might help express the text material's "meaning." In reading, the farther ahead the reader looks, the more elaborate the processing activity can be, and the faster and more fluid the performance (Levin and Addis, 1979). The greater the segment of text perceived and processed at each moment, the greater the possibility of perceiving its syntactic features and other language-based relationships that can result in the

perception of "meaning." Similarly, when a typist copies text, typing speed depends on how far ahead of the words being typed the typist has read (Salthouse, 1991). The same principle applies to reading music from a score (Sloboda, 1985), where musical notation corresponds to words of text and production of the music corresponds to the articulation of words (or locomotion movements or typing of words).

A key aspect of the information made available by looking ahead is the entropy of the perceived stimuli.[3] In the case of reading or copying, entropy can refer to the text's degree of statistical approximation to meaningful language (ranging from normal text at one extreme, as in a newspaper article, to scrambled unweighted letters of the alphabet at the other). The text's entropy for particular individuals evidently also depends on their language skills or familiarity with the text material (Shannon, 1951; Cook, 1972). In the case of locomotion, entropy could be an attribute of the regularity and predictability of the terrain and of the individual's familiarity with it and its perceived features.

In most kinds of learned performance, too, as when we speak, perform music, or execute a dance routine, the motor acts at any instant are always behind the "plan" for the immediately upcoming acts. To draw the analogy with locomotion and the other examples analyzed above, the counterpart of the stimulus train for the upcoming segment would be the covert plan or program for the upcoming motor acts, with the main difference that the covert plan or program would be created in response to largely internal rather than largely external events.[4]

11. Variable contingencies in which the environment changes

In the (self-paced) variable contingencies discussed above, the changes in the external environment are the result of positioning with respect to the environment (as in locomotion, driving a vehicle, reading, or a typist's copying text), and the speed of the individual's

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[3] Claude Shannon (1948, 1951) defined "information" or "negentropy" as the number of yes–no questions that would need to be asked and answered in order to provide the missing information, the unit of entropy being the "bit." The concept of entropy subsumes "predictability", "degree of organization," and "conveyed information content."

[4] It should be noted that the parallels being drawn in the present paper between locomotion and certain complex behaviors are completely separate from the parallels that focus on the sequencing constraints of grammars and syntaxes and the sequencing constraints of most coordinated motor behavior (Roberts, 1978; Bramble and Lieberman, 2004; Kertesz and Hooper, 1982; Kinsbourne, 1978; Ojemann and Mateer, 1979); they are also completely separate from the parallels between phonology and speech production, and certain other motor behavior (Fowler et al., 1980; Lindblom, 1983; Sommerhoff, 1974; Allott, 1989; Lieberman, 2007).

motor behavior affects the rate of progression through that environment. In running, the speed depends to some extent on momentum and the strength and coordination efficiency of body movements, and in reading out loud the speed is somewhat constrained by the relationship between the speed of articulation of the words and their consequent comprehensibility, a constraint that silent reading bypasses.

But there are also important variable contingencies in which movement and flow of the environmental events is unaffected by the individual's behavior. For examples, in listening to music or to a speaker, in simultaneous interpretation (Moser-Mercer, 1997), or in receiving Morse code (Keller, 1958; Keller and Schoenfeld, 1948; Cook, 1972), the counterpart of "looking ahead" is delaying the motor phase until a sufficiently long segment of the stimulus flow has passed, and retaining that segment in memory for time t_1 – long enough for the pp phase to be completed. The same M, E, and F parameters are critical in determining the behavioral effects of such contingencies – the flow rate of the events in relation to the individual's memory capacity and the consequent length of the retained segment, the entropy of the events and the individual's history (experience) with respect to the perceived events (e.g., Cook, 1972), and the relevant physical variables. Claude Shannon (1951) proposed a "guessing game" that demonstrates how the entropy (letter-by-successive-letter predictability) of printed English depends on its statistical approximation to normal English, with newspaper copy at one extreme and unweighted randomized letters of the alphabet at the other.

12. Interactive variable contingencies

Contingencies may also be variable due to interactive effects, where one or more external agents interact with the individual's behavior. Examples are competitive games like tennis or chess, and adversarial activities like physical combat, negotiation, arguing, chasing prey, or fleeing from a pursuer. More social examples include conversation, ensemble music playing, sexual interaction, and team sports. Some examples of such complex contingencies are analyzed in Mechner (2008a,b), but without consideration of the roles of stimulus trains (upcoming or trailing), which are considered in the present paper.

13. Conclusions

A behavioral contingency analysis of locomotion and reading aloud reveals that the motor components of both depend on the prior perception and processing of an upcoming segment, that both use buffering to manage segment variability, that both are subject to the entropy and physical features of the segment, and that both have mechanisms for responding to possible obstacles or other unanticipated stimuli. These parallels suggest that locomotion may be the phylogenetic ancestor and behavioral homologue of certain complex verbal, communication, and performance skills.

It is proposed that the methodology by which these parallels are shown here is generally applicable to the identification of parallels between many other seemingly unrelated behavioral processes like the various types of deception seen in biology and human affairs, biological and social/adversarial situations in which "thinking ahead" is required, and phenomena in economics such as pyramid or Ponzi schemes, lending practices, securities markets, and derivatives. The identification of such parallels may also provide roadmaps for the neural mapping of the behaviors involved.

Acknowledgements

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