

Aging and Changes in Complexity in the Neurobehavioral System

Benoit Rey-Robert, Jean-Jacques Temprado, Eric Berton

UMR 6233 Institut des Sciences du Mouvement E. J. Marey, CNRS & Université de la Méditerranée, Marseille, France

Key words: *aging; complexity; approximate entropy; coupling; cognition; sensorimotor processes.*

Summary. *The issue of complexity is more and more present in numerous domains of biological research, including aging research. In the present paper, based on a selective review of literature, we propose both a conceptual and a methodological framework to address age-related changes in functional complexity of the neurobehavioral system, presumably resulting from modifications of the coupling between cognitive and sensorimotor processes. In particular, after reviewing pioneering and more recent studies on aging and complexity in the neuromusculoskeletal system, we explore the possibility that an age-induced increase in the coupling between cognitive and sensorimotor domains could be captured by a stronger covariation of high-order variables, common to both cognitive and sensorimotor functioning. Our main assumption is that these variables could behave as neurobehavioral markers of aging in the neuromusculoskeletal system. The present approach markedly differs from other traditional approaches, which focused on process-specific variable correlates of chronological age, domain-by-domain, and task-by-task. It provides a coherent conceptual framework, a terminology, and a method for studying age-related coupling of cognitive and sensorimotor processes with the use of complexity and nonlinear dynamical systems theories.*

Introduction

The passage of time in the organism ineluctably leads to structural and functional alterations in its different component subsystems, which result in a decline of performance and loss of behavioral adaptability in many daily living situations. Although various age-induced phenomena occur concomitantly at multiple levels (cells, tissues, organs, functions, and behavior), across different subsystems, and in various task conditions, interactions inevitably occur between functional domains of the neurobehavioral system. Consequently, researchers are forced to adopt a clear-cut theoretical position on the way of dealing with the issue of complexity in the neuromusculoskeletal system and its change during aging. In this respect, an explicit reference to dynamical systems analysis and complexity theories has been made in numerous studies on aging of physiological and neurobehavioral systems during the last 20 years (1–4). Nevertheless, a firm theoretical background remains to be established to make these approaches more attractive in aging research.

Based on a brief survey of the existing literature, the present paper aims to provide a conceptual framework for understanding age-related changes in neurobehavioral complexity, in the theoretical context of analysis of nonlinear dynamical systems.

In particular, we argue that an increased coupling of cognitive and sensorimotor processes observed during aging reflects a loss of complexity in functional organization of the neurobehavioral system, resulting from dedifferentiation of neural processes. Accordingly, new lines of a research agenda are proposed to identify neurobehavioral markers of increased coupling between cognitive and sensorimotor processing during aging.

In the first part of this paper, we present some preliminary statements about classic aging research and the different approaches of biological complexity. In the second part, we show how the study of variability and complexity of behavioral output provides meaningful information about the underlying organization of the aging neurobehavioral systems. Finally, we present new research directions for exploring age-related changes in neurobehavioral complexity by focusing on common markers to cognitive and sensorimotor domain.

Aging Research and Biological Complexity: Some Preliminary Statements Different Approaches of Complexity in the Neuromusculoskeletal System

It is commonly accepted that the neuromusculoskeletal system is a complex system composed of

Correspondence to J. J. Temprado, Institut des Sciences du Mouvement, Université de la Méditerranée, Faculté des Sciences du Sport, 163 Route de Luminy, BP 910, 13288 Marseille cedex, France. E-mail: jean-jacques.temprado@univmed.fr

Adresas susirašinėti: J. J. Temprado, Institut des Sciences du Mouvement, Université de la Méditerranée, Faculté des Sciences du Sport, 163 Route de Luminy, BP 910, 13288 Marseille cedex, France. El. paštas: jean-jacques.temprado@univmed.fr

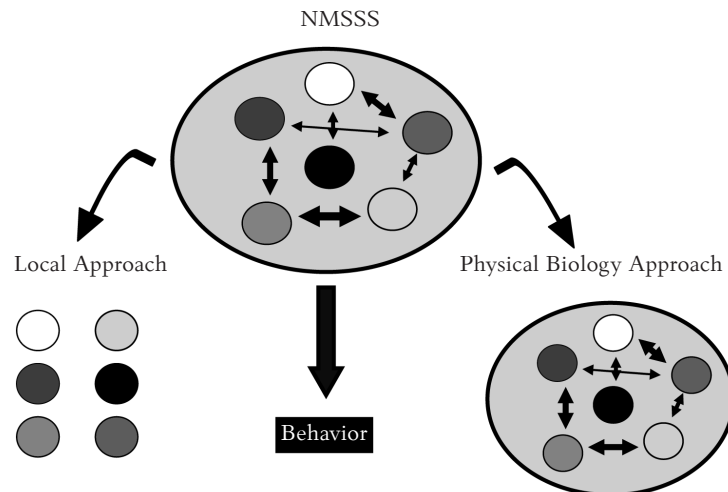


Fig. 1. The neuromusculoskeletal system (NMSS)

It is composed of multiple elements, at different levels, which interact to produce adaptive (i.e., stable and flexible) behavior. The local approach focuses on the study of the components independently. In the physical biology approach, the analysis focuses on the spatiotemporal complexity of behavioral outputs arising from multiple interactions between components.

multiple interacting components at different levels (cells, organs, subsystems, ...). Divergence exists, however, among researchers with respect to whether biological complexity must be considered as a resource or as an obstacle to understanding aging process. Typically, two main theoretical approaches of biological complexity, so-called “local” and “global,” can be distinguished in aging literature.

Proponents of the “local” approach assumed that the neurobehavioral system is decomposable so that the problem of complexity can be solved by dividing it into smaller, simpler, and thus more tractable units (processes, tasks, ...) in separate domains. Accordingly, they consider that age effects operate on multiple juxtaposed spaces and independent time scales, which relegate each subsystems and components to their own causality.

Numerous researchers have however argued that the human neurobehavioral system is more than a collection of static and independent components, governed by simple and linear causalities (3, 5) so that aging ineluctably leads to changes in biological complexity as a consequence of alterations of the different components and their interactions (1). Proponents of this global approach argued that a challenge for aging research is to understand when, how, and why the complexity arising from the interactions of the different systems evolves over time. In this perspective, concerted efforts have been devoted since the early 1990s to establish greater linkages between the different levels of analysis (e.g., brain, information processing, and behavior) (6, 7) or even cross-domain linkages (the coupling of cognitive and sensorimotor processes) (8–10). In parallel, a “physical biology approach” (4), mainly grounded on nonlinear dynamic systems analysis

and complexity theories, has emerged in aging literature (1, 4, 11, 12). The recognition is at the core of this approach that the neuromusculoskeletal system (NMSS) is a self-organizing/self-structuring, multiscale and multilayered system, whose dynamics is driven by chronological age and shaped by constraints arising from multiple sources of various origins (environment, organism, education, life habits, ...), each having its own time scale.

Aging as an Integrated Process Leading to Changes in Behavioral Adaptability

A characteristic feature of healthy biological systems is that they lose their internal robustness and complexity with aging and disease (1, 13). In this perspective, aging can be considered as a dynamic process, reflected in a sequence of (more or less) transient functional states over time. A challenge for researchers is to describe and understand general principles of changes in typical states of neurobehavioral and physiological systems over time. In this perspective, assessing behavioral adaptability, instead of mean performance, is crucial. Behavioral adaptability refers to the capacity of preserving stability and flexibility facing task constraints. These two seemingly conflicting properties may be altered by age-induced alterations of the system components and their interactions. Behavioral adaptability is thus an indirect indicator of underlying changes in functional complexity of the system for researchers and a meaningful property for clinicians (2).

During the last 20 years, the physical biology approach has produced convincing findings and has permitted to identify some general principles of age-related changes in the complexity of the outputs of physiological subsystems (e.g., cardiovascu-

lar system [1]) and task-specific action systems (e.g., grip force control, posture, locomotion, ... see [12] and [14] for extensive reviews). These findings are briefly reviewed in the following chapter.

Aging and Complexity of Physiological and Neurobehavioral Systems **Functional Meaning of Variability of Behavioral Outputs in Complex Systems**

During the last two decades, researchers and clinicians have been progressively aware of the potential applications of dynamical system analysis and complexity theories in the domains of aging and disease (1). It has led to increasing recognition that what appears as white, unstructured, uncorrelated noise in data may possibly be structured in the form of correlation functions in the time and frequency domains (i.e., colored noise). Accordingly, researchers have devoted most efforts to quantification of fluctuations of behavioral outputs by using measures of regularity, randomness, and historicity of time series capturing system behavior. Fluctuations of behavioral outputs represent a coarse grain signature of how the multiple elements interact depending on task-context, timescales, and spaces. In this respect, nonlinear analyses of variability may reveal structures in fluctuations that remain undetected by more traditional measures, such as mean performance changes or standard deviation. Struc-

tured fluctuations possess a great theoretical and clinical significance since they reveal the presence/absence of coupling and characteristic temporal scale that may confer more or less adaptability to the system (1, 15). Thus, the challenge for complexity approaches to aging is to understand the meaning of the modification of structured variability with regard to the functional organization of physiological and neurobehavioral system.

Quantification Time Series Regularity of Behavioral Outputs

Meaningful changes in behavioral variability in healthy aging systems, as well as in clinically relevant syndromes (falling, neurodegenerative disease, ...), are quantifiable by regularity measures. Classically, one considers that healthy systems are those that produce the lower levels of noise (i.e., of stochastic inputs). Thus, variability is primarily considered as reflecting undesirable random noise of varying magnitude, which would be superimposed on an invariant deterministic signal (16). It is noticeable, however, that magnitude and complexity of fluctuations are relatively independent: magnitude of variability may be unaltered whereas complex structure changed.

Instead, when the regulating systems are disturbed within a complex network, as a result of aging or disease, behavioral control may be impaired,

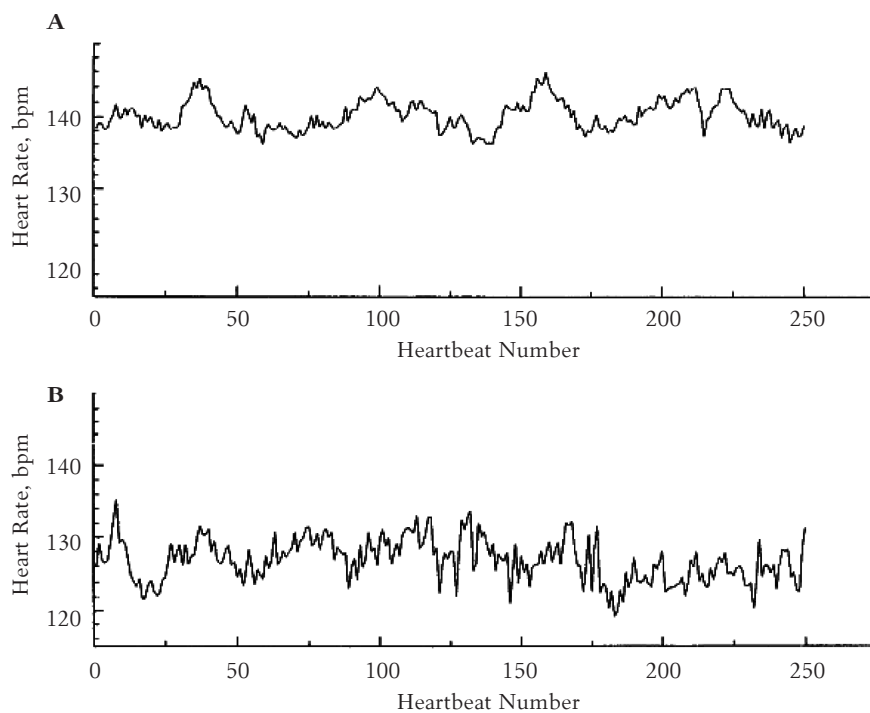


Fig. 2. Comparison of heart rate variability in sleeping children

Magnitude of variability is measured by standard deviation (SD). Structure of variability is captured by approximate entropy (ApEn). Panel A, children with aborted sudden infant death syndrome. Panel B, normal children. One can observe that SD of both time series was equivalent but ApEn significantly differ. See explanations in the text. Adapted from (24).

thereby leading to alterations of multiscale dynamics of fluctuations. Consequently, nonlinear analysis of time series may discriminate physiological or neurobehavioral disorders while other measures may not.

Since complexity of times series is associated with structural richness, to assess it, one quantifies “irregularity” and time dependence of fluctuations in the time series. In this respect, an important methodological challenge is to detect and quantify irregularities, scaling and correlation properties of physiologic and neurobehavioral time series, which are typically nonstationary (see 17 and 18 for detailed descriptions of the different methods). In this aim, multiple nonlinear methods can be used, each having their own interest and limits (e.g., approximate entropy, detrended fluctuation analysis, spectral analysis, or Lyapunov exponent) to capture relative contributions of stochastic and deterministic influences to the change in the system output (19–22).

According to these general principles, two types of measure have been predominantly used in aging research for investigating changes in complexity of physiologic and neurobehavioral system outputs (1, 23). On the one hand, it is approximate entropy (ApEn), which is a measure of the amount of information needed to predict the future state of the system: the larger the entropy, the more irregular the fluctuations, the less predictable the system (1, 22, 24, 25). Typically, the ApEn algorithm returns a value tending toward 2 for highly irregular signals and 0 for highly regular signals. It does not identify, however, the contribution of deterministic and stochastic processes to the observed regularity, and surrogate tests are necessary to rule out the possibility that irregularity reflects random noise. On the other hand, it is fractal scaling exponent calculation (α), which provides an estimation of the “roughness” of the time series and permits to quantify the reliance on history through the presence of time sequential and frequency-dependent properties of time series (self-similarity). Specifically, one considers that the larger the value of the fractal exponent, the smoother the time series. In this context, a value of α equal to 1 (so-called 1/f noise) can be interpreted as the best compromise between complete unpredictability associated with white noise ($\alpha=0.5$) and the much smoother profile of Brownian noise ($\alpha=1.5$). A breakdown in optimal long-range correlation properties in time series is in keeping with the loss of complexity in the system output. Presumably, such breakdown is associated with functional impairment in information transmission and processing in the neurobehavioral system (17).

Aging and the Loss of Complexity Hypothesis

During the last 20 years, knowledge gleaned from seminal studies of physiologic systems (1) has

stimulated dynamical investigations of age-related variability in neurobehavioral systems (12, 26–28). A central assumption for theorizing complexity and aging holds that alterations in the structural and functional properties of the organism lead to a loss of complexity in system outputs and, consequently, in the capacity of the elderly to adapt to various forms of constraints (1, 3, 17, 29, see 23 for a review). This hypothesis was supported by pioneering studies based on the analysis of physiological and neurobehavioral systems (cardiac rhythm, postural control, ...) (1, 24). They showed that healthy systems possess the highest adaptability (healthy) and generate the most physiologically irregular signals. For instance, analysis of scaling behavior in a variety of cardiac pathologies and in healthy elderly people indicated significant alterations in short- and long-range correlation properties (for reviews, see 17, 23). It was noticed, however, that alterations of scaling behavior associated with physiologic aging were different compared with those characterizing heart failure. These findings were consistent with those observed by Lipsitz and Goldberger (1992) using approximate entropy analysis (i.e., a decrease in ApEn in older adults), which suggested a loss of complexity of fluctuations in the time series. Thus, loss of complexity, which is a consequence of age-induced aberrations in the temporal organization of the evolving dynamics, might be a generic feature of aging and a subset of dynamical disease (1, 11).

Since the seminal work done by Lipsitz and Goldberger (1992), approximate entropy and fractal scaling analyses have been used in complex time series of a large variety of subsystems outputs: systolic blood pressure (30), gait (20), electroencephalography (31), center of pressure trajectory in postural control (32), grip force control (33), aiming (34), or even human cognition (35–37). Results confirmed the presence of structured, long-range correlated fluctuations in healthy organisms and supported the hypothesis of systematic breakdown of long-range correlations in behavioral outputs as a result of aging and disease. However, whether or not aging led to a decrease in complexity seemed to depend on a particular dynamic property of the system under investigation. It has led Vaillancourt and Newell (23, see also 4) to propose the “loss of adaptability hypothesis.” They assumed that aging might result in either a decrease or an increase in complexity, as a function of task-specific constraints, both leading to impairment in behavioral adaptability.

Aging and the Loss of Adaptability Hypothesis

In an extensive review of literature, Vaillancourt and Newell (4, 23) examined the universality of the principle of loss of complexity with aging. They suggested that the direction of changes in output

complexity could be system- or task-dependent. More specifically, they showed that in some systems (e.g., the cardiovascular system), a loss of complexity revealed an impaired capacity, and in other systems (e.g., gait, grip force control), an increase in complexity signaled an impairment of control. These findings were counter to the loss of complexity hypothesis, which assumed that the predictability in physiological output should increase with age. Rather, they suggested that there is not a universal principle of directional change in the complexity of behavioral outputs. Instead, change in complexity might depend on the nature of adaptive change required to realize particular system's environment demands. Newell and collaborators (4, 23) distinguished between two types of intrinsic dynamics (resulting from fixed-point and rhythmical attractors), which presumably determine different routes for effective adaptation to a task-specific constraint. On the one hand, fixed-point attractor tasks (attractor dimension = 0) when the system operates around a steady state as for instance in physiological homeostasis (heart rate, hormone secretion, postural control). In this zero dimension attractor, an increase of the system's active degrees of freedom is needed to maintain optimal performance resulting in an increase of the output complexity (higher ApEn). In the case of aging or disease, the impossibility to increase the system's degrees of freedom should result in a reduction in adaptability with a reduced output complexity (lower ApEn). In this case, there is a loss of complexity with aging. On the other hand, Vaillancourt and Newell (23) postulated that for limit-cycle attractor tasks (oscillatory dynamics with attractor dimension = 1) where a decrease in degrees of freedom is required to perform the task, one should observe an increase in complexity with aging and disease (i.e., an increase in ApEn). Indeed, in these tasks, the elderly are unable to decrease the number of active degrees of freedom to perform the task and thus fluctuates more around the intrinsic dynamic resulting in a more complex behavioral or physiological output. Gait cycle or diurnal rhythm of adrenocorticotrophic hormone concentration was a typical example of oscillatory dynamics (20, 38). Vaillancourt and Newell (12) tested this hypothesis in an isometric force production task performed in either constant or periodic (sine wave) conditions. Results showed that structured fluctuations of force output were less complex in old and older-old adults, in the constant force production task, and that they were more complex in the sine wave task. These results confirmed that the directional change of the complexity of physiologic and neurobehavioral system outputs covaries with the dimension of the intrinsic dynamic that organize the system (23).

Behavioral Output Complexity and Functional Organization of the Neurobehavioral System

Though numerous studies supported the hypothesis that change in complexity of behavioral outputs is a generic feature of aging in physiologic and neurobehavioral systems, the question remains how this coarse grain level of analysis of behavioral outputs reflects underlying mechanisms that occur within the neurobehavioral system and gives rise to changes in complexity. In this respect, we contend that more detailed model systems are needed to better establish the relationship between mechanisms that operate within the system and the observed complexity of behavioral outputs (see 39 for a convergent point of view).

According to the current definitions of biological complexity (23, 40), whatever the direction of change in the structured fluctuations of behavioral outputs, change in complexity is hypothesized to result from four (non mutually exclusive) primary mechanisms induced by aging: 1) impairment and/or loss in the number of individual subcomponents of the system; 2) change in the strength of couplings between the components; 3) change in stochastic inputs (e.g., neural noise); and 4) increase in time delays of information transmission within the system (slowing).

However, classic studies on aging were predominantly interested in investigating separately the functional consequences of these different factors on behavioral performance rather than considering them in the perspective of age-related changes in complexity. For instance, impairment of the different individual component subsystems (neuromuscular, cognitive, energetic, ...) and/or loss in the number of components (e.g., loss of neural cells, muscle fibers, white matter, force decrement, ...) have been widely studied in isolation (41–45). The role of stochastic inputs (i.e., neural noise) has also recently been the subject of increased interest in cognitive aging literature through the study of intraindividual variability of performance (7, 46). The issue of behavioral consequences of age-induced increase in time delays of information processes (i.e., the general slowing hypothesis) has been addressed for a long time in cognitive literature (47, 48). However, how changes in these factors affected the complexity of the neurobehavioral system was scarcely addressed in the literature, and consequently, nonlinear measures of structured fluctuations of behavioral performance were rarely considered as meaningful indicators of age-related changes in cognitive or sensorimotor functioning. As noticeable exceptions, recent studies by Delignières and coworkers showed, however, that measures of complexity fruitfully added to the understanding of underlying mechanisms of timing in finger tapping and (loss of)

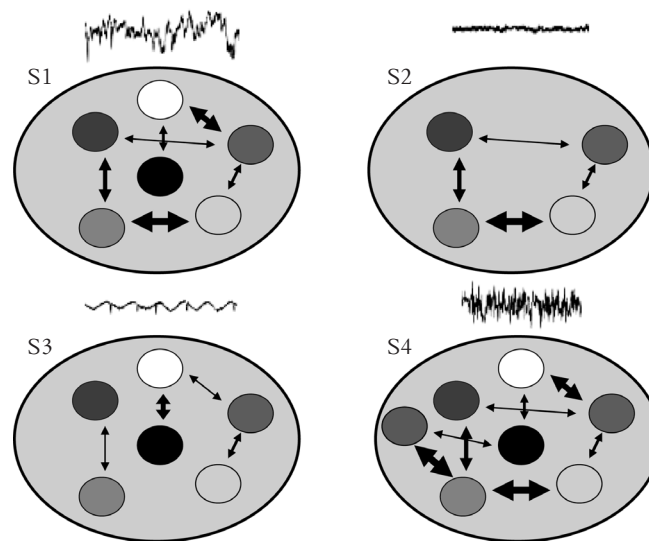


Fig. 3. Simplified representation of the different sources of the loss of adaptability in the neuromusculoskeletal system

S1, the circles represent different interacting components of the NMSS, giving rise to a fixed level of complexity of behavioral output of the whole system. The arrows indicate direction and intensity of their interactions. S2, S3, and S4 illustrate changes in system's complexity resulting from a loss of a component (S1), modifications in the number, intensity, or time delays in the interactions (S3) or an increase in the number of component in the system (S4). Changes in system complexity are expressed in macroscopic patterns of fluctuations of behavioral outputs. Adapted from (2).

stability of bimanual coordination patterns, which were classically assessed by the magnitude of variability (49, 50, see 39 for an overview).

The question remains, however, how complexity approaches can be applied to the study of interactions between subcomponents of the neurobehavioral system that cannot be modeled as nonlinear oscillators as, for instance, the coupling between cognitive and sensorimotor processes. This issue has recently emerged as an important preoccupation in aging research (51, 52). Specifically, it has been suggested that aging was accompanied by a dedifferentiation of cognitive and sensorimotor processes at both brain and behavior, which leads to a stronger coupling between cognitive and sensorimotor abilities (53, see 51 for a review). According to the dedifferentiation hypothesis, aging may be considered an integrated process affecting the whole functional organization of the neurobehavioral system. Consequently, the occurrence of increase in the coupling among the different subsystem components is critical to understanding age-induced changes in the complexity of the neurobehavioral system. We would like to draw some theoretical working hypotheses and methodological procedures in this perspective.

The Coupling of Cognitive and Sensorimotor Processes: a Window for Exploring Age-Related Changes in Neurobehavioral Complexity
Neurobehavioral Markers of Dedifferentiation of Cognitive and Sensorimotor Processes

Ideally, to explore the dynamics of changes in

the coupling of two a priori independent systems (e.g., cognitive and sensorimotor systems), one should be able to collect time series of the signals that represent behavioral outputs of the two systems simultaneously and/or to capture their relationship either by a "collective" variable of the coupling/synchronization pattern (for a general introduction, see 54; see 55 for a detailed example in interlimb coordination) or thanks to nonlinear tools as cross-entropy analysis (56). However, in the case of coupling between cognitive and sensorimotor domains, it is technically difficult since cognitive and sensorimotor systems cannot be assimilated to self-sustained oscillators and does not possess obvious collective variables. Thus, in most experimental paradigms aiming at investigation cognitive-sensorimotor coupling (including double-task paradigms), behavioral time series cannot be simultaneously and continuously recorded.

We argue that an alternative strategy permitting to account for cognitive-sensorimotor coupling lies in the search of common neurobehavioral markers to cognitive and sensorimotor processes, which might permit to assess their time (more and more correlated) coevolution. The underlying neurophysiological justification of this approach is the widely accepted "common cause hypothesis," which assumed that some of the mechanisms that are at origin of age-related decline in cognitive and sensorimotor performance might be shared among different nervous structures in the neurobehavioral system (8, 9, 57). These common structures could mediate the so-called "coupling" between cognitive

and sensorimotor processes in a wide range of tasks. Accordingly, if cognitive and sensorimotor processes become more and more intertwined until forming a single, almost undifferentiated entity in the neurobehavioral system, then it should be possible to identify common markers permitting to assess (to infer) the degree of coupling between cognitive and sensorimotor processes.

What is a Neurobehavioral Marker of Aging?

A neurobehavioral marker of aging is a parameter intended as a quantitative measure of the rate of aging in the neuromusculoskeletal system that represents a more accurate index than chronological age. Moreover, in the absence of disease, it must better predict functional capacity at some later age than will chronological age (58). Accordingly, to be considered as a neurobehavioral marker, any measured variable at brain or behavioral level should tap into the fundamental capacities of the central nervous system (CNS) and summarize its general state (59). According to Deary and Der (60, see also 61, 62), other general characteristics, which might be possessed by the chosen variables to meet the criteria of a neurobehavioral marker aging, are as follows: 1) stable individual differences across several years in large adult samples; 2) a clear pattern of age-related deterioration from young adulthood to old age; and 3) changes from baseline measurement, which are related to mortality and morbidity in longitudinal studies even after adjustment for age.

Examples of behavioral measures that have been used as biomarkers of aging in cognitive and sensorimotor domains were grip strength, blood pressure, visual acuity, or mental processing speed (63). The classic procedure consisted of studying longitudinal correlations of two or more cognitive and sensorimotor measures in order to infer dedifferentiation between the two domains. We contend, however, that to reflect age-related increase in the coupling between cognitive and sensorimotor processes, the most important constraint to the definition of neurobehavioral markers is that they should measure “high order” common phenomena that are observable in both cognitive and sensorimotor domains.

Potential Common Neurobehavioral Markers to Cognitive and Sensorimotor Processes

Even if a general decrease in information processing capacity is not the unique cause of age-related declines in performance of the neurobehavioral system, it presumably explains most of behavioral manifestations of age-related sensorimotor and cognitive changes. Consequently, the following premises can be followed for identifying variables measuring overt behavioral manifestations resulting

from changes in neural resources and information processing capacities in both cognitive and motor domains: 1) the CNS is an information-processing system whose limited central capacity affects both cognitive and sensorimotor functioning, and 2) speed of cognitive and motor behavior are highly dependant on information processing capacity; 3) both cognitive and motor functioning become more reliant on central mechanisms during aging by virtue of increased sharing of neural resources (64, 65), and 4) organization and coupling between components of the CNS change over time, thereby modifying their interactions (23); 5) a decline in general information processing capacities depends on neural processes that are (at least in part) shared by both domains; 6) age-related changes that occur at both neurochemical and neuroanatomical levels of the brain decrease functional information processing capacities in both specific and nonspecific global fashion (47, 64); 7) neural decline in information processing might then “enslave” the evolution of both cognitive and sensorimotor domains, thereby causing correlated behavioral outcomes; 8) dedifferentiation of information processing capacities in cognitive and sensorimotor domains might be reflected in similar overt manifestations, which can be consider as common neurobehavioral markers of their functioning (66–69); and 9) neural noise increases in the information processing system during aging resulting in more inconsistent behavior.

Taken together, the above considerations suggest that (at least) three categories of neurobehavioral markers could capture the coupling between cognitive and sensorimotor coupling: 1) complexity measures of fluctuations of behavioral performance of cognitive and sensorimotor systems; 2) an intraindividual variability measure of behavioral performance; and 3) response speed. Most importantly, since these three makers are supposed to reflect a common cause in the neurobehavioral system, their evolution over age should be increasingly correlated.

Changes in Complexity of Cognitive and Sensorimotor Performance. If change in complexity is a generic feature of aging (4, 23), then changes in structured behavioral outcomes in both cognitive and sensorimotor domains of functioning should be correlated (1). Adequate markers could then be found in entropy and fractal dimension analyses to quantify the complexity of time series of behavioral output in both cognitive and sensorimotor tasks. Correlated changes in complexity should permit to infer underlying modifications of coupling interactions between the components of the system (23). One predicts that directional change in complexity reflecting a loss of adaptability should be similar in both cognitive and sensorimotor tasks.

Time Measures. It is currently admitted that speed is critical to the performance of information processing systems (70). Since rapid responses require an efficient system of communication within the CNS in both cognitive and sensorimotor tasks, speed of processing is commonly considered as an indicator of basic neurocognitive resources (71) and age-related neurological status (48). Accordingly, speed of processing in both cognitive and motor tasks could be a useful neurobehavioral marker of cognitive aging.

Intraindividual Variability Measure. Because neural noise strongly depends on the central command-signal resulting from information transmission and processing, an intraindividual variability of behavioral outcome is also commonly considered as an indicator of basic neurocognitive resources and age-related neurological status (72).

It is noticeable that response speed and intraindividual variability are currently considered as presenting the formal characteristics of biomarkers of aging in cognitive literature (60–62). It remains to be determined whether they are common biomarkers to sensorimotor processes and whether they can reflect the increased coupling between these two functional domains.

How to test Neurobehavioral Markers of Cognitive-Sensorimotor Coupling?

The above-developed theoretical framework leads to a specific research agenda, which is quite different from classic studies in aging research. Indeed, instead of analyzing the coevolution of two specific variables, each measuring behavioral performance in cognitive and sensorimotor domains, it consists of analyzing the correlated changes in common measures to cognitive and sensorimotor processes in different tasks (i.e., performance output complexity, response speed, and intraindividual variability of behavioral performance). The coevolution of these markers is hypothesized to express underlying common causes of age-related changes in behavioral performance. Specifically, if the measured values of each marker evolve in the same direction and are more and more strongly related to age, then it would indicate that the coupling between cognitive and sensorimotor processes increased so that functional capacities tend to be more and more undifferentiated.

To test the coevolution of the values of the different markers, we have to choose representative tasks of cognitive and sensorimotor central information processing capacities. In this respect, reaction time tasks (Hicks' tasks) and unimanual aiming tasks (Fitts' task) are adequate. Indeed, reaction time

tasks permit a measure of the amount of information processed to choose a response (i.e., Hick's law) and have been considered for a long time as representative tasks in the cognitive domain (73). Similarly, Fitts' aiming tasks permit a measure of the amount of information processed to accurately stop the limb on a target (i.e., Fitts' law) and have been considered as representative tasks in the sensorimotor domain (67, 74). Thus, it should be possible to use a common metrics to quantify information processing rates in both cognitive and sensorimotor tasks. Consequently, one could determine whether processing capacities evolve with the same trend during aging, that is, if they become more and more correlated. If affirmative, one could affirm that change in structured fluctuations (i.e., complexity), slowing of motor responses and increases in intraindividual variability were high order markers of the dedifferentiation process. These markers would presumably capture the efficiency of the neurobehavioral system, as a result of increased coupling between cognitive and sensorimotor processes.

Concluding Remarks and Perspectives

Our conviction is that changes in complexity in the neurobehavioral system are the expression of subtle changes, which take place in active (though hidden) dimensions within the system (i.e., freezing/releasing of dynamical degrees of freedom). They lead to modifications of the coupling scheme and its implementation within the neurobehavioral system and, accordingly, its complexity. Searching for common markers of cognitive and sensorimotor aging and exploring their coupled evolution is a new mean for exploring changes in neurobehavioral complexity.

Identification of neurobehavioral markers of aging might have potential clinical applications for simplifying assessment of frailty and cognitive/sensorimotor disease. For instance, correlated changes in these markers might have a predictive value to predict an individual path to a loss of adaptability, frailty, and disease based on their actual values.

A caveat is in order however. At the moment, the complexity paradigm in aging research consists more of a unified way of thinking rather than a finished body of knowledge. Until a general theory appears, it is impossible to tell whether all the pieces of the aging puzzle are at hand that unify the facts well. We hope that the conceptual framework exposed in the present paper will contribute to provide a proper metatheory for aging and firmly establish the complexity approach as attractive and fruitful resources in the field of cognitive and sensorimotor aging.

Senėjimas ir elgseną lemiančios nervų sistemos kompleksiško pokyčiai

Benoit Rey-Robert, Jean-Jacques Temprado, Eric Berton

Valstybinio mokslinių tyrimų centro ir Viduržemio jūros universiteto E. J. Marey judėjimo mokslų institutas, Marselis, Prancūzija

Raktažodžiai: senėjimas, kompleksiškas, apytikrė entropija, ryšys, pažinimas, sensomotoriniai procesai.

Santrauka. Biologinių tyrimų srityje vis dažniau nagrinėjama kompleksiško problema. Ši problema nagrinėjama tiriant ir su senėjimu susijusius klausimus. Šiame straipsnyje, remiantis atlikta literatūros apžvalga, siūlome koncepcinį ir metodologinį modelį, leidžiantį tirti elgseną lemiančios nervų sistemos funkcinio kompleksiško kaitą, sąlygojamą senėjimo ir galimai pasireiškiančią dėl pažinimo ir sensomotorinių funkcijų tarpusavio ryšio pokyčių. Apžvelgę pirmąsias ir pastarųjų metų publikacijas apie senėjimą ir nervų-raumenų-griaučių sistemos kompleksišumą, atskleidėme galimybę senėjimo sukeltus, padidėjusius pažinimo ir sensomotorinių funkcijų tarpusavio ryšio pokyčius nustatyti remiantis aukštesnio rango kintamųjų stipresne kovariacija, kuri būdinga tiek pažinimo, tiek sensomotorinėms funkcijoms. Remiantis mūsų pagrindine prielaida, minėti nervų-raumenų-griaučių sistemos kintamieji gali elgtis kaip neuroelgseniniai senėjimo ženklai.

Taigi, siūloma metodika labai skiriasi nuo kitų tradicinių metodikų, kurios orientuotos į atitinkamas proceso kintamųjų koreliacijas, atsižvelgiant į chronologinį amžių, parametras po parametro ir užduotis po užduoties. Ji teikia nuoseklią koncepciją, terminologiją ir metodiką, kuri nagrinėja su senėjimu susijusių pažinimo ir sensomotorinių funkcijų tarpusavio ryšio pokyčius, remiantis kompleksinių ir netiesinių dinamiškų sistemų teorijomis.

References

- Lipsitz LA, Goldberger AL. Loss of 'complexity' and aging. Potential applications of fractals and chaos theory to senescence. *JAMA* 1992;267(13):1806-9.
- Vaillancourt DE, Newell KM. Changing complexity in human behavior and physiology through aging and disease. *Neurobiol Aging* 2002;23(1):1-11.
- Peng CK, Costa M, Goldberger AL. Adaptive data analysis of complex fluctuations in physiologic time series. *Adv Adapt Data Anal* 2009;1(1):61-70.
- Newell K, Vaillancourt D, Sosnoff J. Aging, complexity and motor performance. In: Birren J, Schaie K, editors. *Handbook of the psychology of aging*. London: Elsevier Academic Press; 2006. p. 163-78.
- Ahn AC, Tewari M, Poon CS, Phillips RS. The limits of reductionism in medicine: could systems biology offer an alternative? *PLoS Med* 2006;3(6):e208.
- Bäckman L, Nyberg L, Lindenberger U, Li SC, Farde L. The correlative triad among aging, dopamine, and cognition: current status and future prospects. *Neurosci Biobehav Rev* 2006;30(6):791-807.
- Li SC, Lindenberger U, Frensch PA. Unifying cognitive aging: from neuromodulation to representation to cognition. *Neurocomputing* 2000;32-33:879-90.
- Heuninckx S, Wenderoth N, Debaere F, Peeters R, Swinnen SP. Neural basis of aging: the penetration of cognition into action control. *J Neurosci* 2005;25(29):6787-96.
- Heuninckx S, Wenderoth N, Swinnen SP. Systems neuroplasticity in the aging brain: recruiting additional neural resources for successful motor performance in elderly persons. *J Neurosci* 2008;28(1):91-9.
- Li KZH, Lindenberger U. Relations between aging sensory/sensorimotor and cognitive functions. *Neurosci Biobehav Rev* 2002;26(7):777-83.
- Glass L, Mackey M. *From clocks to chaos: the rhythms of life*. Princeton: Princeton University Press; 1988.
- Vaillancourt DE, Newell KM. Aging and the time and frequency structure of force output variability. *J Appl Physiol* 2003;94(3):903-12.
- Li SC, Huxhold O, Schmiedek F. Aging and attenuated processing robustness. Evidence from cognitive and sensorimotor functioning. *Gerontology* 2004;50(1):28-34.
- Newell KM. Schema theory (1975): retrospectives and perspectives. *Res Q Exerc Sport* 2003;74(4):383-8.
- Sosnoff JJ, Valentine AD, Newell KM. Independence between the amount and structure of variability at low force levels. *Neurosci Lett* 2006;392(3):165-9.
- Hultsch DF, MacDonald SWS, Dixon RA. Variability in reaction time performance of younger and older adults. *J Gerontol B Psychol Sci Soc Sci* 2002;57(2):101-15.
- Goldberger AL, Amaral LAN, Hausdorff JM, Ivanov PC, Peng CK, Stanley HE. Fractal dynamics in physiology: alterations with disease and aging. *Proc Natl Acad Sci U S A* 2002;99 Suppl 1:2466-72.
- Goldberger AL, Peng CK, Lipsitz LA. What is physiologic complexity and how does it change with aging and disease? *Neurobiol Aging* 2002;23(1):23-6.
- Duarte M, Zatsiorsky VM. On the fractal properties of natural human standing. *Neurosci Lett* 2000;283(3):173-6.
- Hausdorff JM, Mitchell SL, Firtion R, Peng CK, Cudkovic ME, Wei JY, et al. Altered fractal dynamics of gait: reduced stride-interval correlations with aging and Huntington's disease. *J Appl Physiol* 1997;82(1):262-9.
- Ladislao L, Fioretti S. Nonlinear analysis of posturographic data. *Med Biol Eng Comput* 2007;45(7):679-88.
- Pincus SM. Approximate entropy as a measure of system complexity. *Proc Natl Acad Sci U S A* 1991;88(6):2297-301.
- Vaillancourt DE, Slifkin AB, Newell KM. Inter-digit individuation and force variability in the precision grip of young, elderly, and Parkinson's disease participants. *Motor Control* 2002;6(2):113-28.
- Pincus SM, Goldberger AL. Physiological time-series analysis: what does regularity quantify? *Am J Physiol* 1994;266(4 Pt 2):1643-56.
- Pincus SM. Approximate entropy as a measure of irregularity for psychiatric serial metrics. *Bipolar Disord* 2006;8(5 Pt 1):430-40.
- Slifkin AB, Newell KM. Noise, information transmission, and force variability. *J Exp Psychol Hum Percept Perform* 1999;25(3):837-51.
- Slifkin AB, Newell KM. Variability and noise in continuous force production. *J Mot Behav* 2000;32(2):141-50.

28. Sosnoff JJ, Newell KM. Age-related loss of adaptability to fast time scales in motor variability. *J Gerontol B Psychol Sci Soc Sci* 2008;63(6):344-52.
29. Costa M, Priplata AA, Lipsitz LA, Wu Z, Huang NE, Goldberger AL, et al. Noise and poise: enhancement of postural complexity in the elderly with a stochastic-resonance-based therapy. *Europhys Lett* 2007;77:68008.
30. Kaplan DT, Furman MI, Pincus SM, Ryan SM, Lipsitz LA, Goldberger AL. Aging and the complexity of cardiovascular dynamics. *Biophys J* 1991;59(4):945-9.
31. Elger CE, Lehnertz K. Seizure prediction by non-linear time series analysis of brain electrical activity. *Eur J Neurosci* 1998;10(2):786-9.
32. Ramdani S, Seigle B, Lagarde J, Bouchara F, Bernard PL. On the use of sample entropy to analyze human postural sway data. *Med Eng Phys* 2009;31(8):1023-31.
33. Sosnoff JJ, Valantine AD, Newell KM. The adaptive range of 1/f isometric force production. *J Exp Psychol Hum Percept Perform* 2009;35(2):439-46.
34. Wijnants ML, Bosman AMT, Hasselman F, Cox RFA, Orden GCV. 1/f scaling in movement time changes with practice in precision aiming. *Nonlinear Dynamics Psychol Life Sci* 2009;13(1):79-98.
35. Gilden DL. Cognitive emissions of 1/f noise. *Psychol Rev* 2001;108(1):33-56.
36. Orden GCV, Holden JG, Turvey MT. Human cognition and 1/f scaling. *J Exp Psychol Gen* 2005;134(1):117-23.
37. Wagenmakers EJ, Farrell S, Ratcliff R. Estimation and interpretation of 1/f noise in human cognition. *Psychon Bull Rev* 2004;11(4):579-615.
38. Pincus SM, Mulligan T, Iranmanesh A, Gheorghiu S, Godschalk M, Veldhuis JD. Older males secrete luteinizing hormone and testosterone more irregularly, and jointly more asynchronously, than younger males. *Proc Natl Acad Sci U S A* 1996;93(24):14100-5.
39. Torre K, Wagenmakers EJ. Theories and models for 1/f(beta) noise in human movement science. *Hum Mov Sci* 2009;28(3):297-318.
40. Chauvet G. *La vie dans la matière: Le rôle de l'espace en biologie. (Life in material: the role of space in biology.)* Chauvet G, editor. Paris: Champs Flammarion; 1995.
41. Devaney KO, Johnson HA. Neuron loss in the aging visual cortex of man. *J Gerontol* 1980;35(6):836-41.
42. Meier-Ruge W, Ulrich J, Brühlmann M, Meier E. Age-related white matter atrophy in the human brain. *Ann N Y Acad Sci* 1992;673:260-9.
43. Doherty TJ, Vandervoort AA, Taylor AW, Brown WF. Effects of motor unit losses on strength in older men and women. *J Appl Physiol* 1993;74(2):868-74.
44. Lexell J. Human aging, muscle mass, and fiber type composition. *J Gerontol A Biol Sci Med Sci* 1995;50:11-6.
45. Spear PD. Neural bases of visual deficits during aging. *Vision Res* 1993;33(18):2589-609.
46. Hultsch DF, MacDonald SW, Hunter MA, Levy-Bencheton J, Strauss E. Intraindividual variability in cognitive performance in older adults: comparison of adults with mild dementia, adults with arthritis, and healthy adults. *Neuropsychology* 2000;14(4):588-98.
47. Cerella J. Generalized slowing in Brinley plots. *J Gerontol* 1994;49(2):65-71.
48. Salthouse TA. The processing-speed theory of adult age differences in cognition. *Psychol Rev* 1996;103(3):403-28.
49. Delignières D, Torre K, Lemoine L. Long-range correlation in synchronization and syncope tapping: a linear phase correction model. *PLoS One* 2009;4(11):e7822.
50. Torre K. The correlation structure of relative phase variability influences the occurrence of phase transition in coordination. *J Mot Behav* 2010;42(2):99-105.
51. Schäfer S, Huxhold O, Lindenberger U. Healthy mind in healthy body? A review of sensorimotor-cognitive interdependencies in old age. *Eur Rev Aging Physic Activ* 2006;3:45-54.
52. Baltes PB, Lindenberger U. Emergence of a powerful connection between sensory and cognitive functions across the adult life span: a new window to the study of cognitive aging? *Psychol Aging* 1997;12(1):12-21.
53. Lindenberger U, Ghisletta P. Cognitive and sensory declines in old age: gauging the evidence for a common cause. *Psychol Aging* 2009;24(1):1-16.
54. Pikovsky A, Popovych O, Maistrenko Y. Resolving clusters in chaotic ensembles of globally coupled identical oscillators. *Phys Rev Lett* 2001;87(4):044102.
55. Kelso J. *Dynamic patterns: the self-organization of brain and behavior.* Kelso J, editor. Cambridge: MIT Press; 1995.
56. Pincus SM. Greater signal regularity may indicate increased system isolation. *Math Biosci* 1994;122(2):161-81.
57. Li S, Lindenberger U. Cross-level unification: a computational exploration of the link between deterioration of neurotransmitter systems and dedifferentiation of cognitive abilities in old age. In: Nilsson L, Kirkland W, editors. *Cognitive neuroscience of memory.* Kirkland, WA: Hogrefe & Huber; 1999. p. 103-46.
58. Baker GT, Sprott RL. Biomarkers of aging. *Exp Gerontol* 1988;23(4-5):223-39.
59. Madden DJ. Neuroimaging of memory. Introduction. *Microsc Res Tech* 2000;51(1):1-5.
60. Deary IJ, Der G. Reaction time explains IQ's association with death. *Psychol Sci* 2005;16(1):64-9.
61. Shipley BA, Der G, Taylor MD, Deary IJ. Association between mortality and cognitive change over 7 years in a large representative sample of UK residents. *Psychosom Med* 2007;69(7):640-50.
62. Shipley BA, Der G, Taylor MD, Deary IJ. Cognition and all-cause mortality across the entire adult age range: health and lifestyle survey. *Psychosom Med* 2006;68(1):17-24.
63. Christensen H, Mackinnon AJ, Korten AE, Jorm AF, Henderson AS, Jacomb P, et al. An analysis of diversity in the cognitive performance of elderly community dwellers: individual differences in change scores as a function of age. *Psychol Aging* 1999;14(3):365-79.
64. Seidler RD, Bernard JA, Burutolu TB, Fling BW, Gordon MT, Gwin JT, et al. Motor control and aging: links to age-related brain structural, functional, and biochemical effects. *Neurosci Biobehav Rev* 2010;34(5):721-33.
65. Sosnoff JJ, Newell KM. Are age-related increases in force variability due to decrements in strength? *Exp Brain Res* 2006;174(1):86-94.
66. Hick WE. On the rate of gain of information. *Quart J Exp Psychol* 1952;4:11-26.
67. Fitts PM. The information capacity of the human motor system in controlling the amplitude of movement. *J Exp Psychol* 1954;47(6):381-91.
68. Seow SC. Information theoretic models of HCI: a comparison of the Hick-Hyman law and Fitts' law. *Human-Computer Interaction* 2005;20:315-52.
69. Zhai S. Characterizing computer input with Fitts' law parameters: the information and non-information aspects of pointing. *International Journal of Human-Computer Studies* 2004;61:791-809.
70. Myerson J, Adams DR, Hale S, Jenkins L. Analysis of group differences in processing speed: Brinley plots, Q-Q plots, and other conspiracies. *Psychon Bull Rev* 2003;10(1):224-37.
71. Macdonald SWS, Hultsch DF, Dixon RA. Predicting impending death: inconsistency in speed is a selective and early marker. *Psychol Aging* 2008;23(3):595-607.
72. Macdonald SWS, Dixon RA, Cohen AL, Hazlitt JE. Biological age and 12-year cognitive change in older adults: findings from the Victoria Longitudinal Study. *Gerontology* 2004;50(2):64-81.
73. Welford AT. Signal, noise, performance, and age. *Hum Factors* 1981;23(1):97-109.
74. Fitts PM, Peterson JR. Information capacity of discrete motor responses. *J Exp Psychol* 1964;67:103-12.

Received 15 October 2010, accepted 6 January 2011
 Straipsnis gautas 2010 10 15, priimtas 2011 01 06