Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in Behavioral Sciences

It's not (only) the mean that matters: variability, noise and exploration in skill learning

Dagmar Sternad

Mastering a motor skill is typified by a decrease in variability. However, variability is much more than the undesired signature of discoordination: structure in both its distributional properties and temporal sequence can reveal control priorities. Extending from the notion that signal-dependent noise corrupts information transmission in the neuromotor system, this review tracks more recent recognitions that the complex motor system in its interaction with task constraints creates high-dimensional spaces with multiple equivalent solutions. Further analysis differentiates these solutions to have different degrees of noise-sensitivity, goal-relevance or additional costs. Practice proceeds from exploration of these solution spaces to exploitation with further 'channeling' of noise. Extended practice leads to fine-tuning of skill brought about by reducing noise. These distinct changes in variability are suggested as a way to characterize stages of learning. Capitalizing on the sensitivity of the CNS to noise, interventions can add extrinsic noise or amplify intrinsic noise to guide (re)-learning desired behaviors. The persistence and generalization of acquired skill is still largely understudied, although an essential element of skill. Consistent with advances in the physical sciences, there is increasing realization that noise can have beneficial effects. Analysis of the non-random structure of variability may reveal more than analysis of only its mean.

Address
Department of Biology, Electrical & Computer Engineering, and Physics, Center for the Interdisciplinary Study of Complex Systems, Northeastern University, Boston, MA, United States

Corresponding author: Sternad, Dagmar (d.sternad@northeastern.edu)

Current Opinion in Behavioral Sciences 2018, **20**:183–195

This review comes from a themed issue on **Habits and skills**

Edited by **Barbara Knowlton** and **Jörn Diedrichsen**

https://doi.org/10.1016/j.cobeha.2018.01.004

Variability and noise in skill learning: bad or good?

Learning new motor skills is quintessentially human. Over our lifetime we learn to eat with knife and fork, ride a bicycle, and dance salsa, going far beyond the fundamental locomotory and reaching behaviors that all animals display. How can the neuromotor system achieve such extraordinary plasticity, flexibility, and creativity? Over the last decades there has been relatively little research in motor neuroscience on the acquisition of novel motor skills, in favor of research on more constrained movements under highly controlled conditions. For example, a widely used experimental platform has been reaching of a 2-link arm in the horizontal plane with meticulously designed perturbations that introduce force fields or visuomotor mappings to induce adaptation [1,2]. When neuroimaging is involved, the tasks necessarily have to be even further reduced to small finger and hand movements. While experimental reduction and control has a long history in motor neuroscience and is core to any empirical science, the perennial risk is that the real problems are 'controlled away'. One such phenomenon that is intentionally attenuated by experimental control is variability. This review aims to draw attention to the fact that variability and noise in motor performance is not only a nuisance, but is a ubiquitous and informative biological feature that has meaning in itself, not only to the performer but also to the scientist who aims to understand movement control and coordination.

Trying to understand skill learning inevitably has to face variability. Mastering a new motor skill implies performing with increasing accuracy and diminishing variability, or 'with maximum certainty and a minimum outlay of time or energy' [3–6]. Similarly, recent work showed that skill improvement manifests in a shift of the speed–accuracy trade-off function [7,8]: skilled individuals become less variable, while keeping the same tempo, or they can move faster without increasing variability. And yet, not even Olympic athletes ever perform with total certainty — like robots. In fact, this is what makes competitive sports interesting to watch. Why are humans not perfect? The complex neuromotor system has abundant noise and fluctuations at all levels [9,10], and even deterministic physiological processes at lower levels may manifest in overt unstructured 'noise'. Hence, skill cannot, and probably should not completely suppress noise. Rather, it should 'make noise matter less' [11,12], that is, have little or no effect on task success. Further, variability is necessary when exploring solutions for a novel task. So, can noise be beneficial? The plethora of roles and meanings of variability is also reflected in a variety of seemingly similar and overlapping terms (see Table 1). While there are no strict definitions, the table attempts to reserve different labels for different aspects of variability. The fact that variability and noise is a phenomenon that is

Table 1

Overview of terminology with brief definitions.

Variability and variation	Umbrella terms for all sets or series of observations that are non-constant and may be also non-stationary.
Variance	Well-defined concept in statistics that measures spread of data from its mean, quantified as squared deviation of a random variable from its mean.
Noise	Unstructured variability, both in the temporal and spatial domain. In signal processing it is defined as a random signal with equal intensity at different frequencies, i.e., constant spectral density at all component frequencies (white noise).
Colored noise or 1/*f* noise	Signals with power spectral densities proportional to $1/f^{\beta}$; for Brownian noise $\beta = 2$. Note, the signal is still noise, but has different degrees of predictability.
Uncertainty	Originating in probability theory and Bayesian literature, the term is defined as possible states or outcomes measured by assigning probabilities to each possible state or outcome, including probability density functions for continuous variables.
Fluctuations	Non-constant behavior over time that can be stochastic or deterministic. Time series with sinusoidal changes and more than one frequency components are fluctuations, but are not stochastic. The degree of structure is measured with metrics measuring 'complexity', e.g., entropy.
Deterministic versus	System or process whose outcome is entirely determined by inputs and initial conditions, no randomness involved in the development of future states.
Stochastic processes	Random sequence or selection of data that have no structure in the temporal or spatial domain.
Isotropic versus	Distribution is uniform in all directions.
Anisotropic distributions	Distribution is non-uniform in different directions.

interesting and intricate has already been recognized by many other physical sciences [13]. This review aims to demonstrate and argue that variability is rich in information about control priorities in skill learning and maybe even more meaningful than the mean.

Adaptation versus *de novo* learning

Before reviewing variability in skill acquisition, a distinction needs to be drawn between *de novo* learning and adaptation: evidently, not every movement is a novel skill that needs practice to be mastered. Adaptation of well-established behaviors such as postural control, locomotion or reaching to altered environmental demands epitomizes essential behavioral capacity ubiquitous in daily life. Adaptation has received much attention over recent decades in experimental paradigms such as prism, visuomotor, or force-field adaptations. However, it should not be confused with *de novo* learning as its behavioral manifestations are markedly different, suggesting different underlying processes. Figure 1a illustrates the typical time course of adaptation: in laboratory experiments few trials are sufficient to approximate the new target and in real life it has to happen almost instantly and accurately, for example, when grasping a cup that is fuller than expected. The process reduces an externally induced error back to zero-error performance, probably reducing sensory prediction errors, modeled by linear time-invariant systems [14]. This fast change contrasts to the weeks and months of practicing and fine-tuning a new skill, such as handwriting or learning to dance salsa (Figure 1b). An even longer process is motor development unfolding over the timescale of years [15,16]. Several essential elements of skill acquisition play only a subordinate role in adaptation: Exploration of new solution spaces is relatively modest (see below [17]); generalization, essential for any learning, tends to be limited as adaptation occurs fast in new situations [18,19]; adapted behaviors quickly vanish when the perturbation disappears [20], despite savings upon renewed exposures. For skills long-term retention is essential and any intervention not only aims to accelerate the slow process of improvement but also to achieve retention (Figure 1c). Unlike in adaptation, variability plays many different roles in skill learning and is an umbrella term for a plethora of conceptually distinct observations that are non-constant and non-stationary (see Table 1).

This review focuses on acquisition of perceptual-motor behaviors that are novel, demanding and complex with inherent redundancy that offers a space of multiple solutions that need to be explored and learned. The review begins with the traditional notions of noise as unwanted signal corruption to more recent perspectives how motor variability can reveal the structure of control, and can characterize stages of learning, and finishes with how noise may be leveraged in training interventions.

Noise as nuisance

Dating back to Woodworth [21] in the late 1900s and a prominent concept since the advent of information theory [22] in the 1950s, noise has been regarded central to understand communication in signal and symbol processing systems, such as the brain and the neuromotor system. Undisputedly, neural signals in the body have noise that can corrupt the information transmission. To assure veridical information transmission, it is necessary to minimize noise and thereby increase the signal-to-noise ratio. Directly motivated by information theory,