ARTICLE

Changing Up the Routine: Intervention-Induced Variability in Motor Learning

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RANGANATHAN, R. and K.M. NEWELL. Changing up the routine: intervention-induced variability in motor learning. *Exerc. Sport Sci. Rev.*, Vol. 41, No. 1, pp. 64–70, 2013. *Variability is often introduced by an external agent (e.g., an instructor) during practice with the purpose of enhancing motor learning. Using a task analysis approach, we provide a framework to examine the effects of intervention-induced variability. We propose that variability may have markedly different consequences on learning depending on the task level at which it is introduced.* **Key Words:** redundancy, schema, variable practice, structure learning, differential learning, exploration, specificity

INTRODUCTION

The notions of skill and variability are often interpreted as being inversely related. An archer who hits the target but has a large spread in the distribution of where the arrows land would not be considered to be very skilled. Therefore, definitions of motor skill usually emphasize not only a high level of performance but also consistency (or low variability) in achieving this high level of performance (9). Although this emphasis on reducing variability is defined at the level of the movement outcome (*e.g.*, the dispersion of where the arrows land), there is sometimes an implicit assumption that low variability in the outcome can only arise from low variability in the movement execution (*e.g.*, the kinematics of the arm). This assumption leads to the idea that variability in movement execution is detrimental to skill, as evidenced by the common practice of training to achieve consistent movement patterns.

In this regard, research in motor control and neuroscience has shown that some degree of variability is actually necessary for motor learning and skill. Several studies have suggested that variability is important for exploration (18) and is especially critical for reinforcement learning (33). In other words, having a certain degree of movement variability provides a repertoire of actions from which we can select to adapt successfully to changes both in our body and in the environment. This has been observed in rehabilitation of locomotion where robotic training that allows a certain degree of kinematic variability of the limbs results in better outcomes compared with following a fixed trajectory with low variability (35). Moreover, variability is present even in skilled performers — the classic example in motor control is from Bernstein (3), who showed how the hammer trajectories of expert blacksmiths exhibited a functional variability in that they were variable but, at the same time, also converged to hit the target. These and other studies (2) have led to the hypothesis that movement variability is critical for performance in both novices and skilled athletes (6) , and there might be an intermediate amount of variability (neither too much nor too little) that is required for optimal functional performance (10).

However, an important question that arises is, "Does this evidence mean that practice schedules need to include variability to facilitate learning?" A major caveat in using the preceding evidence is that, although it suggests that variability is critical to learning and skill acquisition, a large part of the evidence cited has focused on what could be termed "intrinsic motor variability," that is, variability that is inherent in the motor system when performing the task. This distinction is important because the variability that an external agent (*e.g.*, a coach or a therapist) introduces, using methods such as instructions, is usually at least an order of magnitude larger than the inherent motor variability in the system. For example, although there is variability in skilled athletes, these movement variations are often quite small in magnitude and it very well could be that they are effectively attempting to reproduce the same movement while having the ability to compensate for small deviations. Therefore, from the

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perspective of the external agent who wants to facilitate motor learning, the question of how induced movement variability affects learning is critical.

In this review, we examine the effects of intervention-induced movement variability on motor learning. We use the term "intervention-induced" to refer to variability that is introduced by an external agent (distinguishing it from intrinsic motor variability). In particular, we develop a framework that shows that movement variability may have very different effects on motor learning depending on the task level at which it is introduced. We also show how this framework can be used to integrate previous approaches to variability and provide a systematic way to examine the effects of intervention-induced variability on motor learning. Finally, we consider conditions under which inducing movement variability can be detrimental to learning.

FRAMEWORK TO EXAMINE INTERVENTION-INDUCED VARIABILITY

The term "variable practice" has been used in the literature to describe a wide range of conditions of variability induced during practice. These usually refer to introducing different variations of a single skill but also sometimes to practice scheduling (contextual interference) that deals with the question of how to optimize the learning of multiple skills. Here, we focus on variations of the former kind, that is, how different variations can be introduced to facilitate the learning of a single skill. The original formulation of variable practice was based on the idea of a generalized motor program in schema theory (25) and is one of the most tested predictions of schema theory (17). However, the manipulation of generalized motor program parameters (relative force and relative timing) is restricted to a small set of tasks and becomes problematic especially when using tasks requiring the coordination of multiple degrees of freedom. Therefore, here we provide a framework to distinguish different levels at which variability can be introduced in tasks that allow multiple solutions (22).

Our framework is based on the observation that there is redundancy in most motor tasks, that is, there are multiple ways to execute a movement to achieve the same task goal. This redundancy is present at several different levels in the system: multiple trajectories to reach the same external location in space, multiple joint configurations to produce the same end-effector location, multiple muscle activations to produce the same joint configuration, and so on. At this stage, we can introduce variability broadly at two levels: 1) variability in the task goal and 2) variability in the execution redundancy (Fig. 1). On one hand, variability in the task goal level implies that the induced movement variations are intended to cause different task outcomes. On the other hand, variability in the execution redundancy level implies that induced movement variations are intended to cause the same task outcome (*i.e.*, explore the redundancy in the task). We use the term "intended" because although the external agent may design the task to introduce variability at one level, the actual execution of the movement by the participant may be inaccurate and imprecise, especially in the early stages of learning.

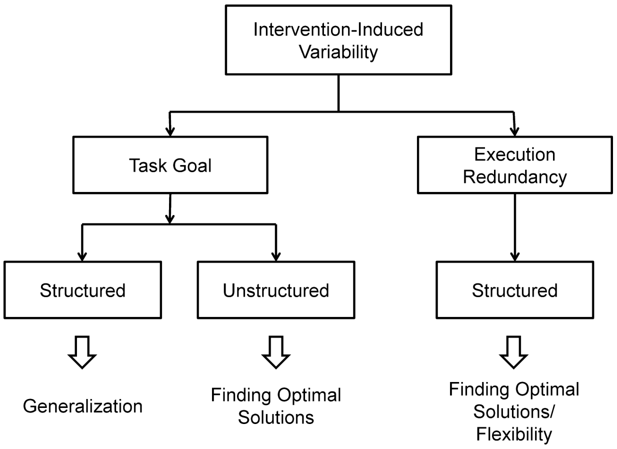

Figure 1. Schematic diagram showing how intervention-induced variability can be introduced at two different levels of the task — the task goal level and execution redundancy level. The variability introduced can also be structured (systematic variations of one or few parameters) or unstructured (random variations of multiple parameters). The potential benefits of these manipulations on motor learning (generalization, optimal solutions, and flexibility) are specified with each approach in the text.

The distinction between introducing variability at these two levels is illustrated in Figure 2. Consider the example of a basketball player trying to shoot a basket from the free throw line that is 15 ft away (29). On one hand, an example of variation in the task goal level would be to change the distance between the player and the basket (10 ft, 15 ft, 20 ft). Changing this distance would require the player to use different movement solutions to achieve these different task outcomes (Fig. 2A). On the other hand, variations at the execution redundancy level would involve having the basket at the same position relative to the player but finding different solutions to get the ball in by exploring different ball trajectories to throw the ball from the same distance (Fig. 2B). These variations could be induced, for example, through verbal instructions or by appropriately placing obstacles so that the player has to find different solutions of satisfying the same task outcome. Thus, variations at the execution redundancy level emphasize the exploration of different movement solutions to achieve the same outcome.

Figure 2 also depicts the solution manifold on the right in both these cases. The solution manifold represents the movement solutions that can be used to successfully achieve the task goal. For example, the contour labeled 15 ft shows all possible velocity-angle combinations of the ball that lands the ball in the basket 15 ft away (indicating the redundancy in the task). On this solution manifold, the distinction between the two levels is clear: variations in the task goal are intended to push the participant away from the 15-ft contour. However, variations in the execution redundancy level are intended to push the participant along the 15-ft contour.

It is important to note that the definition of the task goal needs to be specific so that the two levels of variability are clearly defined. For example, in Figure 2A, if the task goal was a higher level task goal such as "get the ball in the basket," then it would seem like changing the location of the basket was only a manipulation at the execution redundancy level because the task goal (of getting the ball into the basket) is unchanged. To

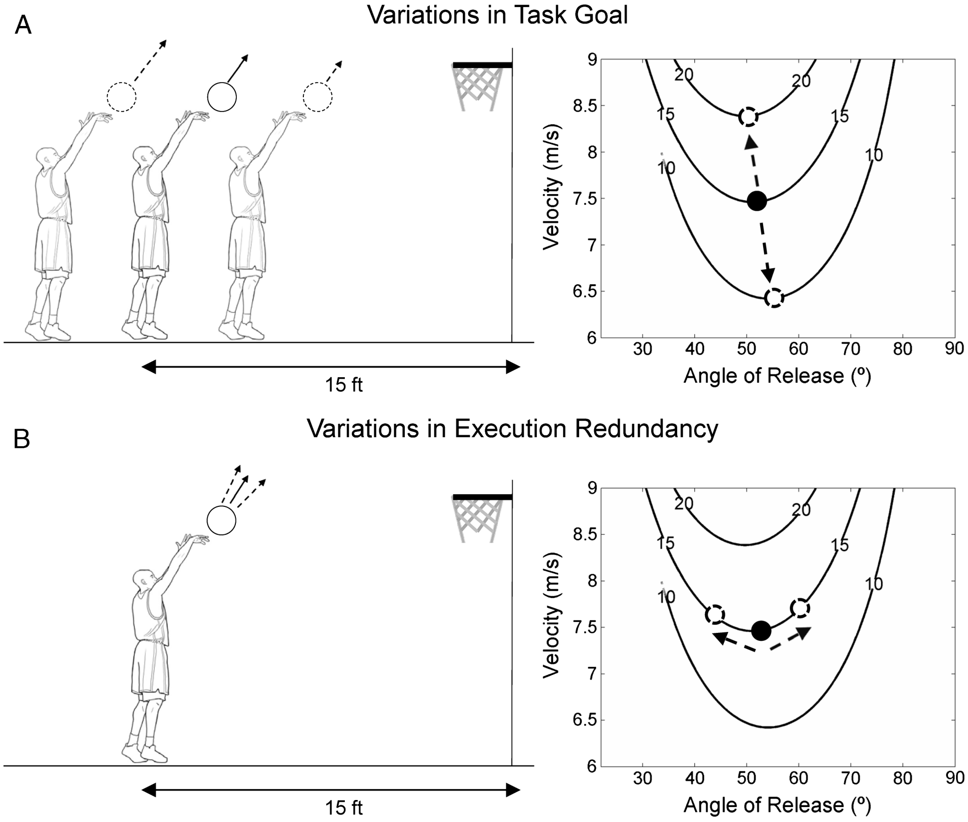

Figure 2. Introducing variability at two different levels in a basketball free throw task (regulation distance of 15 ft). A. At the task goal level, variability can be introduced by having the participant throw from different distances to the basket (*e.g.,* 10 ft, 15 ft, and 20 ft). This results in participants having to change their solutions because they have to achieve different task goals. B. At the execution redundancy level, variability is introduced by encouraging participants to find different solutions to the same task goal of 15 ft. On the *right* of each figure, the solution manifold for this task is shown. This solution manifold describes velocity-angle combinations at ball release (shown as *contours*) that would be successful in achieving the 10-ft, 15-ft, and 20-ft distances. Variations at the task goal level are intended to move the participant away from the 15-ft contour, whereas variations at the execution redundancy level are intended to move the participant along the 15-ft contour. The solutions depicted here are based on the equations of projectile motion (neglecting air resistance) and the assumption of the basket as a point target (*i.e.,* the size of the hoop and the backboard are neglected). This point target is assumed to be located 1 m (~3.28 ft) above the point of ball release. Figure is not to scale.

avoid such confusion, the task goal should be specific enough so that it should be possible to construct a solution manifold such as the one shown in Figure 2 (also see (30)). Therefore, if the task goal is defined as "get the ball in the basket that is 15 ft away," then a solution manifold can be readily constructed, identifying the different velocity-angle combinations that would lead to an outcome of 15 ft (as shown in Fig. 2). Although it is not necessary (or may not be possible) to analytically derive the solution manifold in every task, the definition of the task goal should be precise enough that one can at least hypothetically construct the set of movements that will lead to successful execution of the task (and conversely, the set of movements that will lead to task errors).

This distinction between the task goal level and the execution redundancy level discussed here maps to the notion of the task space and null space (also referred to as goal-relevant and goal-equivalent manifold (5)) and has been used in studies (15,27,32) to infer control mechanisms. However, these approaches have not focused on introducing variability at different levels during practice. Moreover, it has to be noted that our framework itself is not tied to any specific theoretical assumptions of these approaches; for example, the idea that null space variability is "good" may not be true from the viewpoint of motor learning because exploring the null space variability during practice can sometimes be detrimental to learning and retention (20).

INTEGRATING PERSPECTIVES ON INTERVENTION-INDUCED VARIABILITY

In this section, we integrate previous theoretical constructs on intervention-induced variability in our framework and examine how variations at the two different levels cause different effects on motor learning.

Effects of Variations at the Task Goal Level

Variations at the task goal level can be classified into two categories: 1) structured variations, and 2) unstructured noise-like variations (Fig. 1). Both of these have been used for different purposes in motor learning — with structured variations generally being used for improving generalization and transfer to novel conditions, whereas unstructured variations are used to facilitate the search for a more optimal solution to perform the same task.

Structured variations of task goal parameters typically involve manipulating a task goal parameter in a specified range, usually with the goal of improving generalization to other task variations. These variations are referred to as "structured" because variations are made systematically in one or a few parameters (as opposed to random variations of multiple parameters described as "unstructured" variations). In the basketball example, setting the basket at different distances during practice would be one such manipulation. This type of parameter variation is common to many approaches that involve extracting "invariants" or "abstract rules" from these variations and is most typical in the variable practice schedules derived from schema theory. In general, there is evidence (also see (34)) that practicing with systematic variations at the task goal level leads to improved generalization and transfer to novel task conditions and may also involve different neural substrates (12). The explanation for these effects of variability on learning is that practice variability improves the association between the movement parameters and the task outcome, resulting in the development of an abstract rule that can be generalized to other unpracticed conditions (25).

More recently, variable practice at the task goal level also has been expanded in the perceptual-motor domain, where it has been shown that different variations of the task goal can be used to facilitate the participant to attend to the most relevant variables required to complete the task (11). Relatedly, there is also evidence that apart from learning movement parameters, variation may also help participants with structural learning. For example, when participants practiced in an environment with variation in the visuomotor rotation angle, this facilitated the ability to adapt to any visuomotor rotation, indicating that the variations facilitated the participant to infer that the environment was one of the visuomotor rotations (4). These results suggest that structured variability in the task goal can lead to generalization and may be important in task contexts where transfer to novel task conditions is an important aspect of learning (such as rehabilitation).

A second way of introducing variations at the task goal level is to use unstructured variations, where parameter variations are introduced across multiple parameters of the task simultaneously, analogous to introducing "noise" in the system. From a dynamic systems perspective, these noise-like variations may improve performance by shifting performance out of a local minimum (26). The goal of this manipulation is to facilitate exploration of movements that could result in the system finding a more optimal solution to do the same task, for example, when attempting to break through a plateau in performance. This concept of introducing noise to improve performance has been demonstrated in the sensory domain and is referred to as stochastic resonance (19). In motor learning, this approach has been termed differential learning and has been used in several tasks, like shot put throwing, to improve performance (reviewed in (8)). In this approach, noise-like variations are introduced by having participants perform very different movements from trial to trial, with the variations introduced across multiple different parameters. For example, in the shot put experiment, these variations included changing the direction of the throw, changing initial and final body configurations, changing the timing of different body segment rotations, and varying the grip from trial to trial (8).

In a similar vein, noise-like variations have also been introduced through noninvasive brain stimulation and found to improve the performance of a thumb acceleration task (31). Here, the authors specifically showed that theta-burst stimulation over the motor cortex resulted in greater motor output variability at the thumb, which facilitated greater exploration and greater performance gains. The observation that the benefits of these stochastic noise manipulations are generally seen in tasks that require the generation of rapid maximal effort movements suggests that these variations at the task goal level may be important in cases where finding the right coordination pattern to execute a specific task is critical to performance and where generalization to other task conditions is not as critical (such as track and field sports).

Effects of Variations at the Execution Redundancy Level

Contrary to the many different perspectives that rely on variations at the task goal level, variations at the execution redundancy level have been much less used in motor learning. Nevertheless, manipulation at this level could also be considered a form of exploration, but this exploration is by definition structured because the variations can only be in the family of movements that all satisfy the same task goal. In addition, although studies of motor learning test learning through retention and transfer tests, this manipulation also allows the assessment of another component of motor learning — flexibility. In other words, can participants quickly find alternative solutions when a well-practiced solution is no longer feasible? A preliminary hypothesis is that exploring multiple solutions to perform a task could have two effects on learning: 1) it could lead to the emergence of a more optimal solution because there is an element of exploration and 2) it could also improve flexibility by allowing participants to use alternative solutions in cases where certain solutions are not feasible because of changes in either the body or the environment.

We recently performed a series of studies (21,22) that examined the importance of exploring this redundancy during aiming tasks (Fig. 3). Practice was designed toward either

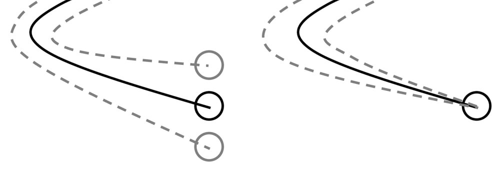

Figure 3. Variability at the task goal and execution redundancy levels in an interception task. The *small circle* depicts the start point and the *larger circle* depicts the target that participants are aiming for. The *curved paths* are caused by the presence of a virtual obstacle between the start point and the target. At the task goal level, participants use different paths to hit different targets, whereas at the execution redundancy level, participants use different paths to hit the same target. [Adapted from (22). Copyright © 2010 The Authors.]

using different movement paths to hit different targets (*i.e.*, the task goal level) or exploring different paths to hit the same target (*i.e.*, the execution redundancy level). Participants in different groups had 1 d of practice at this task, and we examined two aspects of learning: generalization and flexibility.

The results clearly revealed that manipulations at the two levels were not just quantitatively different but qualitatively different, as well. With regard to generalization, only the group that practiced multiple targets (*i.e.*, variations at the task goal level) was able to generalize to targets across the whole workspace, whereas the group that practiced multiple paths to hit a single target was unable to do so. In a separate experiment, we examined whether practicing multiple paths resulted in improved flexibility compared with practicing paths with low variability. However, contrary to our expectations, we found that flexibility was actually higher for the group that practiced with a low path variability (21), possibly because of this group having a very good representation of where the target was located. Although these results seem to suggest that practicing multiple solutions does not facilitate flexibility, more research is essential to fully understand how variations at the execution redundancy level facilitate motor learning.

More generally, the differences between variations at the task goal and the execution redundancy levels also have implications for hypotheses attempting to explain the benefits of variable practice. One plausible hypothesis for the benefits of introducing variability during practice is that variable practice conditions require greater attention to the task, thereby increasing cognitive demands and creating conditions similar to contextual interference (16). Although the generality of the contextual interference effects is still under debate (24), the prediction from this line of reasoning is that as long as the same movement is not repeated, introducing variability at any level should yield similar outcomes. However, the results from our studies show that this is not the case. Therefore, although cognitive demands may have an important influence, the level at which variability is introduced plays a critical role in how variability affects motor learning.

CAN INTERVENTION-INDUCED VARIABILITY BE DETRIMENTAL TO LEARNING?

So far, we have discussed ways in which introducing variability at different levels can facilitate motor learning. However, at both task goal and execution redundancy levels, there are conditions under which introducing movement variability might hamper motor learning. In fact, there has been a long-standing debate as to whether practicing a consistent movement pattern can be superior to variable practice under certain conditions (28). In particular, there are two issues that need to be considered that could result in worse outcomes when variability is induced: 1) use-dependent learning and 2) coordination pattern stability.

Use-Dependent Learning

First, there is a mechanism of motor learning that is use dependent (7). In other words, this learning mechanism tends

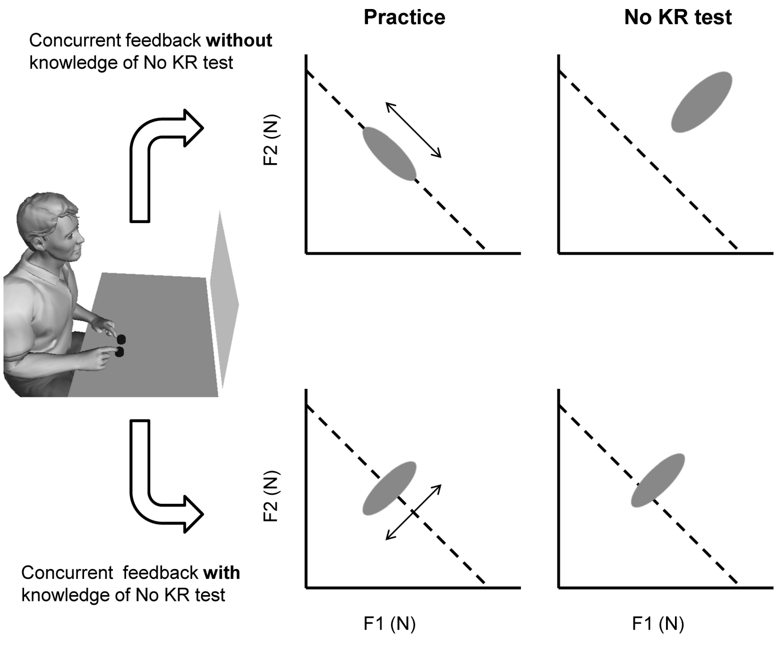

Figure 4. Role of variability in coordination pattern stability. Schematic diagram of an experiment where participants were attempting to produce discrete pulses of force using their two fingers to match a peak total force of 10 N. Participants were given concurrent feedback of the total force output during practice and tested in a No-Knowledge of Results (No-KR) test at the end of practice. (*Top*) When participants were unaware of the No-KR test, they oriented their variability along a direction that was optimal for performance (as indicated by the *arrows*). However, this coordination mode that was used during practice is not stable in the absence of feedback and consequently results in poor performance in the No-KR test. (*Bottom*) When participants were informed about the No-KR test in advance, they oriented their variability along a direction that could be sustained without feedback even though it was suboptimal for performance (as indicated by the *arrows*). This resulted in participants being able to retain this performance in the No-KR test when feedback was removed. The *dotted line* shows the different force combinations of the two fingers (*F1*, *F2*) that result in a total force of 10 N. [Adapted from (20). Copyright © 2009 The Authors.]

to make subsequent movements similar to previous movements that have been performed. This is similar to the notion of the buildup of a perceptual trace of the movement that gets stronger with practice (1). Support for this hypothesis has been found through trial-to-trial analysis where, despite variability, there is a tendency for successive movements to be similar with learning (23). This use-dependent mechanism could also explain the notion of "especial skills," where well-practiced movements show a certain degree of specificity. For example, in skilled basketball players, performance at free throws from the regulation distance (*i.e.*, the 15-ft free throw line) is greater than that predicted from performance at nearby distances (13). Because this use-dependent mechanism depends on making similar movements, it may be weakened in conditions where participants have excessive variations introduced from trial to trial. Therefore, although many learning approaches discourage "rote repetition of movements" (16), such practice actually could be useful in contexts where there is a need to reduce variability of a particular movement pattern. However, this improvement through repeated practice may come at the cost of poor generalization to other task goal variations (22).

Coordination Pattern Stability

A second issue when introducing variability is that of movement pattern stability. Although stability has been operationally well defined in bimanual coordination (14), there is the notion in many movement contexts that there exist certain coordination patterns that are preferred or "stable" in that they are easily reproducible with a low variability. In this regard, having practice conditions that result in introducing variability along an "unstable" direction could lead to maladaptive coordination patterns that affect subsequent learning. We recently demonstrated an example of such maladaptive behavior in bimanual force control (20). Participants produced discrete force pulses with two fingers to match the total peak force to a specified target force (10 N). All participants had concurrent feedback of the total force being produced during practice. In this context, we induced movement variability in different directions by manipulating information about the availability of feedback. We manipulated whether participants knew before practice that they had to perform in a No-Knowledge of Results (No-KR) test at the end of practice. On one hand, when participants were unaware of the No-KR test, they oriented their variability along a dimension that was optimal for performance (15), but this coordination pattern was unstable in the absence of visual feedback. This resulted in large errors when performing in the No-KR test (Fig. 4, top panel). On the other hand, when participants were told about the No-KR test (which presumably increased the emphasis on forming a coordination pattern that was stable even in the absence of visual feedback), they oriented their variability so that they performed a stable coordination pattern even though it increased their performance error (Fig. 4, bottom). Therefore, ensuring movement stability is an important consideration when introducing variability and may be especially important in the beginning stages of the skill where practice of unstable coordination patterns could result in poor learning.

SUMMARY

Many instructors, coaches, and therapists are interested in the question, "Does introducing movement variability during practice facilitate learning?" In our view, this question does not have a simple yes or no answer. We propose that it is important to move away from the notion of considering variability as a single construct (and the associated umbrella term "variable practice") because introducing movement variability during practice can influence learning in multiple ways through multiple mechanisms. In this article, we have outlined a framework that provides a systematic basis for studying the effect of intervention-induced variability on motor learning. We show how introducing variability may have different effects on learning (generalizing to novel conditions, finding optimal solutions, increasing flexibility) depending on the level (task goal or execution redundancy) at which it is introduced. Future experiments are needed (especially at the execution redundancy level) to understand the mechanisms of how variability at these different levels affects motor learning.

Given our framework, the following may be important questions for future research:

- Are different types of motor skills (*e.g.*, tasks that emphasize speed vs those that emphasize accuracy) facilitated to different extents by introducing variability at different levels?
- How does introducing variability at different levels interact with skill level (*e.g.*, the stage of acquiring a novel coordination pattern vs the stage of scaling an already acquired pattern)? How does the amount of variability introduced during practice influence this relation?
- Given that there is a change in intrinsic motor variability with age and pathology, how does the influence of variability at different levels interact with these factors?

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