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The ontological status of task constraints: implications for research and practice

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HIGHLIGHTS

- Task constraints have a distinct ontology compared to other constraints categories
- We propose task constraints as soft constraints (a cost/performance function)
- Soft constraints influence, rather than channel, behavior
- Task constrains are formalized in terms of learned- and experimenter-framed spaces

ABBREVIATIONS

C	Constraints
DF	Degrees of freedom
E	Elbow
EA	Elbow adduction
EF	Elbow flexion
ER	Elbow rotation
EΘ	Elbow angle
HT	Target height of the tray
HX	Hand position x axis
HY	Hand position y axis
HZ	Hand position z axis
HΘ	Hand orientation angle
MAX(HY)	Maximum height of customers heads
M	Number of elements
N	Number of dimensions
S	Shoulder
SA	Shoulder adduction
SF	Shoulder flexion
SR	Shoulder rotation
SΘ	Shoulder angle
VT	Target view of the tray
V	View of the tray
W	Wrist
WA	Wrist adduction
WF	Wrist flexion
WR	Wrist rotation
WΘ	Wrist angle

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ABSTRACT

BACKGROUND: Coherent and ordered movement patterns emerge from the many available degrees-of-freedom and constraints channeling the interactions between them and the environment.
AIM: We propose that task constraints have a different ontological status compared to the constraint categories of the environment and organism.
METHODS: We argue that environmental and organismic constraints can be characterized as hard constraints as they are alternative descriptions of the dynamics (i.e., they describe the boundaries and characteristics of the system). Task constraints can, instead, be categorized as soft constraints–functions that influence the behavior toward task relevant solutions. Individuals search through the task space (function relating performance and movement parameters) encompassing rules and goal description but, only through learning, do the task constraints become actualized. Thus, in this manuscript, we discuss the ontology of task constraints elaborating how they should be discussed in the literature.
CONCLUSION: This modified interpretation leads to an expansion of the concept into two frames (learner-based, experimenter-based) that has a series of consequences to future research on motor behavior.

KEYWORDS: Dynamical systems | Skill acquisition | Motor learning | Motor development | Motor control | Search-strategies

INTRODUCTION

> "The claim on which we are converging, ideally, is this: The order in biological and physiological processes is primarily owing to dynamics and that the constraints that arise, both anatomical and functional, serve only to channel and guide dynamics; it is not that actions are caused by constraints it is, rather, that some actions are excluded by them" [1].

The quotation above captures one of the main pillars of the dynamical systems approach to motor behavior. It is through the interaction of multiple constraints, arising between and within many levels of analysis, that *order* (coordination) emerges in action. A theory based on such a coalition of constraints [2] explains behavior without invoking the tenets of the representation-prescriptive perspective. It follows that the concept of constraints is one of the most important for the dynamical systems approach to motor behavior (see [1,3,4]).

Forty years ago, Karl Newell [5,6] proposed three categories of constraints: environmental, organismic and task. Newell's list of environmental and organismic constraints would be imposed parameters and relations within body/environment that bound perception-action possibilities. Environmental and organismic constraints were already considered in the evolving ecological approach to perception and action (see, for instance [7]). Task constraints (task rules, implements, and goals) were the kind of constraints that were necessary to link potential informational variables to be attended with appropriate actions for intention to be fulfilled.

Despite the increasing use of the construct of task constraints in the literature (see, for instance [8,9]), how rules and goals of the task constrain perception and action is still elusive. As we will argue in the present text, task constraints have a different ontology when compared to the categories of constraints (environmental and organismic). While organismic and environmental constraints describe the dynamical status of the organism and the surrounding environment (i.e., how the organism and environment channels behavior through a set of boundaries [equations of constraints]), task constraints are a description of how the perception-action couplings demonstrated in a given task must be evaluated (similar to a cost function). In this line of thinking, task constraints are continuously *driving* behavior towards a given set of solutions while organismic and environmental constraints are always present. Therefore, task constraints are of a different "nature" (ontology) than environmental and organismic constraints. Because theories of motor behavior are almost always evaluated within a given task (or similar set of tasks), in order to truly grasp general principles of motor behavior we must consider this "special" nature of task constraints. This would avoid conclusions overly specific to the task constraints at hand or the stage of practice being observed–an ongoing problem in the area (see, for instance [10,11]).

This need for reinvesting on constraints ontology does not comes only from us. Balagué et al. [12] also proposed a different view on the relation between task and the other categories of constraints. For them, task constraints are emergent from the interactions between environment and organism (considering individual and social drivers of intentions to act/ "creating" tasks) and there are different timescales of influence in behavior. We agree. Nonetheless, their view does not capture the necessary consideration on how such emergent category of constraints (that we maintain, and they do not) differentially modifies behavior.

In this paper, we outline a case for the idea of hard and soft constraints that would allow an understanding of how task constraints interact with motor behavior in general. It is our view that task constraints can be better understood when considering rules and goals as forming a task space that individuals perceive and act accordingly when practicing and performing. It follows that to understand how task constraints influence behavior, one must examine the motion of individuals in the task space; that is, how individuals search in this space [13,14]. Within this view, we propose that, with practice, individuals perceive and act more in line with the task space (see [15,16]). We develop the position that the task space needs to be considered in terms of different frames, experimenter- and learner-based, so one can understand how individuals are influenced by task constraints.

The present manuscript falls within a long-term inquiry in psychology; namely, how tasks and goals modify behavior. For instance, Tolman [17] considered goals as a center piece in mental representations encompassing the likelihood of achieving them. From our point of view, such mental estimation is not needed as the likelihood of achieving a goal emerges from the ongoing interaction of the individual and the task–being directly available. A related influence here is the work of Fleishman [18] that saw underlying commonalities on (what he called) task characteristics (or dimensions) that would favor the understanding of human factors influencing performance. The current work brings back these task characteristics to the center stage but, also, expands on them by speculating about how these would influence behavior.

BRIEF REVIEW ON CONSTRAINTS

Before developing the task constraints construct, we briefly outline what constraints are and how their interaction channels order in the dynamics of motor behavior. This introduces the topic sufficiently as background for our subsequent development of task constraints as soft constraints (for more elaborated discussions on constraints and their origins in biological systems, see [1,19,20]).

We will use an example to illustrate how constraints fit into common situations of daily life. Imagine a waiter having to move around in a restaurant with a tray full of food so that restaurant goers, while sitting at their table, can see what is on the tray. The tray must be always oriented in the horizontal to avoid the food from falling on the floor. Also, it must not be held at a height too high so that the customers cannot see what is on the tray, but it should not be held too low so as to hit the seated individuals' heads. The best height will be the one that induces more customers to ask for the food. As we explain the various categories of constraints, we characterize them in terms of this example of a waiter.

In line to the initial quotation of this manuscript, Newell [5] stated that "Constraints may be viewed as boundaries or features that limit motion of the entity under consideration. […] The rate with which constraints may change over time varies considerably with the level of analysis and parameter under consideration" and, citing [1], "descriptions of constraints are essentially no more than alternative accounts of the degrees of freedom, although constraints may or may not reduce the number of degrees of freedom." Let us unpack the characteristics described in these quotes.

Degrees of freedom, broadly speaking, are the coordinates necessary to describe the configuration of a system or body position [21]. In our example, the task refers to the position of the tray (its height and orientation in two axes): we need basically three variables; thus, we have three degrees of freedom. However, as the tray does not provide much information in terms of how our body achieves such a configuration, we are also interested in the motion of the arm, forearm and hand positions, or even the shoulder, elbow and wrist angles. To describe the position of someone's arm in space in terms of its joints' angles, we would start by saying that the individual has, at least, three joints (i.e., wrist, elbow and shoulder) moving in three dimensions (flex/ extend, adduct/ abduct and internally/ externally rotate) and, thus, nine degrees of freedom (s_f, s_a, s_r, e_f, e_a, e_r, w_f, w_a, w_r), where *s, e,* and *w* represent shoulder, elbow and wrist angles, respectively, in their three dimensions *f* [flexion]*, a* [adduction]*,* and *r* [rotation]). Additionally, we would need to keep track of the position of the hand in the air (h_x, h_y, h_z, representing the hand central position and the three spatial axes). To count degrees of freedom, multiply the number of elements by the number of dimensions being considered–here we have [12].

For completeness, we should mention that an important aspect that we are not discussing here is the issue of frame of reference. We are currently describing the degrees of freedom in terms of an external observer in a Cartesian geometry. This might not be appropriate in physiological terms: it might be necessary to properly understand how the system stipulates reference points, metrics and geometry to generate a definitive theory on how constraints emerge and direct behavior (see, for instance, [22,23])

Knowing a little about these joint motions, we see that the number of degrees of freedom that we need to keep track of is reduced. That is, the shoulder is the only joint in the arm complex that can move in three dimensions (note, that this assumption already simplifies the shoulder joint complex); the elbow (and the radioulnar joint) can flex/extend and pronate/supinate only and the wrist can flex/extend, adduct and abduct. Then, some of the degrees of freedom outlined above are constrained to not move (their equations are set to zero). The equations that relate degrees of freedom or set them to given values are equations of constraint. In the present case, thus, we have two equations of constraint:

$$e_a = 0,\ w_r = 0$$

Additionally, given there is a fixed distance between adjacent joints, the hand position can be fully determined by the joint angles (equations not shown for simplicity). When equations of constraint are equalities based on positions (such as the ones above), they are said to be holonomic. Holonomic constraints, given their nature, decrease the number of functional or active degrees of freedom [6,24]. To consider the number of constraints in calculating the number of degrees of freedom, from the number of elements times the number of dimensions, we subtract the number of holonomic constraints. More succinctly, $m * n - c = DF$, where *m* is the number of elements, *n* is the number of dimensions, *c* is the number of constraints and *DF* is the resultant number of degrees of freedom. Here, then, we have 7 degrees of freedom (9 degrees of freedom of the joints plus 3 of the hand-position minus the 2 equations on the joints and 3 of the hand position).

From here, we can start to unpack Newell's [5] statements on constraints. Note that, in stating that some motions do not occur for some joints (and distances between joints are fixed), we are basically simplifying the whole relation of ligaments, muscles and bones and assuming limited change in them. These anatomical constraints only work for an anatomic range of forces that the musculoskeletal system can support. In this way, the equations of constraint "imposed" on the system above are just alternative descriptions of the dynamics of the musculoskeletal system. That is, there is no imposition of constraints. Constraints are descriptions of limits and relations that emerge from lower levels.

The above constraints can also be said to be *scleronomic*. This means that they do not change over time (i.e., they are independent of time). Clearly, this depends on the time-scale of the analysis being performed. If we are studying motor development, we will inevitably consider changes in body segments' size (and other important measures such as inertia, mass, strength) that will affect how behavior occurs. In our example, we would need to keep track of the distances between joints, for instance. This is not the case when investigating the effect of practicing 60 trials of the waiter presentation on the same day. If the constraints are dependent on time, they are said to be *rheonomic.*

Remember that Newell[5] also stated that constraints could be *boundaries* to behavior and might not decrease the degrees of freedom. This usually occurs when the constraints are *non-holonomic*. Basically, any equation of constraint that does not meet the premises of being an equality and based on positions are called non-holonomic. In our example, we can describe all joint range limits: that is, the limits to the motion of the joints' angles. For instance, the waiter can extend his wrist up to 85º and flex up to -90º (assuming 0º to be the neutral position). That is, $-90^{o} \geq e_f \geq 85^{o}$. Such an equation does not decrease the degrees of freedom given that we still need to consider all 7 degrees of freedom previously counted; the equation only limits the range of values that the wrist can show.

We will now consider the waiter in a 2D space (the sagittal plane) so as to decrease the complexity of the problem. Figure 1 shows a schematic of the waiter's body, arm and the joint angles considered together with the types of constraints that can be observed. Here we have three joints that can only move in a single dimension (flex/extend, now denominated w_θ, e_θ, s_θ), the position of the hand, in two dimensions (h_x, h_y), and their constraints. Note that, given we are using the shoulder position as the frame of reference, the hand position is fully described by the joint positions and segment lengths as well as the hand orientation, we have only 3 degrees of freedom to consider.

These exemplary constraints are highly important as they account for a range of aspects in quite complex movement patterns (see Holt et al.[25] for an example on how muscle-skeletal constraints account for many aspects of gait). However, these constraints are not sufficient to "explain" observed movement patterns given many details of movements would need to be specified by an extraordinary agent if only biomechanical constraints were available.

A given is that to reach a goal, we must be able to perceive and act accordingly [26]. For instance, in our example, the individual must perceive (using haptics) how to, in terms of the distribution of weight on the tray, maintain the tray sufficiently horizontal. This requires covarying joints' angles as to maintain the wrist in a given orientation to the ground. Also, he/she must be able to navigate around chairs, tables and persons walking around the restaurant through optic flow and adaptations to their walking pattern.

Speculatively, if the waiter does not possess given structural and functional properties, he/she would not be able to maintain the tray in the same way. Specifically, without a haptic system, for instance, the individual would not be able to use any informational variable that can be perceived through this system and, thus, actions would be organized differently. The contrary is also the case: if he/she had a "super" perceptual system able to avoid obstacles without needing to use vision, he/she would modify how actions are guided using this "super" system. Through a more general statement, the way we perceive and act is constrained by structural and functional properties of the body.

Additionally, the way we perceive and act in a given timepoint in life is constrained by historical developmental and learning experiences. That is, the way one will perform a given task is largely driven by previously learned perception and action cycles that the environment affords. In our example, this means that while some waiters might prefer to stiffen their joints to dampen any perturbation, others will compensate by moving joints in ways that the tray maintains its horizontal orientation (for more on intrinsic tendencies and strategies see [27–29]). These tendencies are also due to the evolutionary time scale of the species, favoring attention to specific variables and coupling with action possibilities [30].

Such constraints on perceiving and acting set boundaries on how an individual can achieve certain goals. These constraints are not biomechanical in the same sense of the constraints imposed in the joint range of motion. Nevertheless, these clearly constrain how individuals interact with the environment. These constraints emerge from the many micro levels of the human body and are constrained by the emergent functions they give rise to [1,31,32]. In this sense, constraints are not limited to a single level of analyses and are clearly cause and effect of different levels interacting–the macro-order emerges from micro level interactions (constraints) that, in their turn, are constrained by the emergent macro-order (reciprocal/circular causality, see [33]). It is important to note that this cause and effect refers to the emergence of constraints from other levels of analyses rather than stating that constraints are a direct cause of any outcome (at any level).

More importantly, action and perception constrain each other in the sense that the way one moves allows detection of given energy patterns (e.g., optical flow, smell gradient) that guide given actions (e.g., walking, search for a prey)–the perception-action cycle. It is important to emphasize that perception-action constraints (or couplings) are time-dependent (rheonomic) given the system is always in need to change perception-action modes as goals and tasks change over time (see [34]). The perception-action couplings (emergent constraints) have been viewed as softly-assembled provided they occur given intentional, informational, functional and task aspects[31]. Indeed, the emergence of these macro constraints is what makes the concept so important for the dynamical systems approach: Given a set of constraints and a given parameter regime, ordered behavior emerges. The implied circular causality of constraints (macro-order constraints but, at the same time, emerges from micro interaction constraints, see [33]) and their nested nature (see [10]) fulfill the requirements for stability and flexibility.

From these many constraints, the number of *functional* (active, dimensional, dynamical) degrees of freedom that are required to describe behavior are few [35–37]. It is, then, that if *control* is required, it occurs at this level of analysis–given coordination *emerges* from the constraints of the agent-environment system[1]. Clearly, control here is taken as the usual colloquial meaning – a volitional capacity of central nervous system to direct actions/movement parameters. Also, given how the system interacts with the environment that surrounds us (i.e. environmental constraints)–and that we are dissipative, nonlinear, open systems–perception-action couplings can be stable and, in this way, are apt to base actions in an ever-changing/perturbing environment.

TASK CONSTRAINTS AS SOFT CONSTRAINTS

The categorization of the multitude of aspects of an action into three broad categories of constraints [5] stimulated the need to identify what would be relevant parameters of the organism, environment and task for the acquisition of a given skill. "Constraints" have become an umbrella term for any type of parameter in action–especially in explaining unexpected differences between experimental conditions (within and between articles). However, *stating* that something is a constraint does not provide the reason why things differ. One must specify *how* such constraints alter perception-action couplings resulting in a new observed behavior.

The particular case, that will be developed here, is the task constraints category. At first look, the task constraints provide the utility of a given perception-action coupling in a given task as this determines if the goal of a given action will be achieved (as a cost/utility function). Thus, one is able to understand the perception-action cycle employed when task constraints are considered. The issue, nevertheless, is that task constraints, contrary to the other two categories, are not directly actualized (i.e., "make actual, realize" [38])–at least not in their entirety. That is, in most cases of motor learning, learners demonstrate perception-action couplings that are not going to result in success (realizing task constraints) and, for this reason, they fail to realize the goal. In fact, motor learning occurs as individuals change in the direction of actualizing the task constraints. Individuals learn to attend to the most useful variables (e.g.,[39,40]) and modify their actions (e.g.,[41,42]) to improve performance and, after practice, be successful–actualize task constraints.

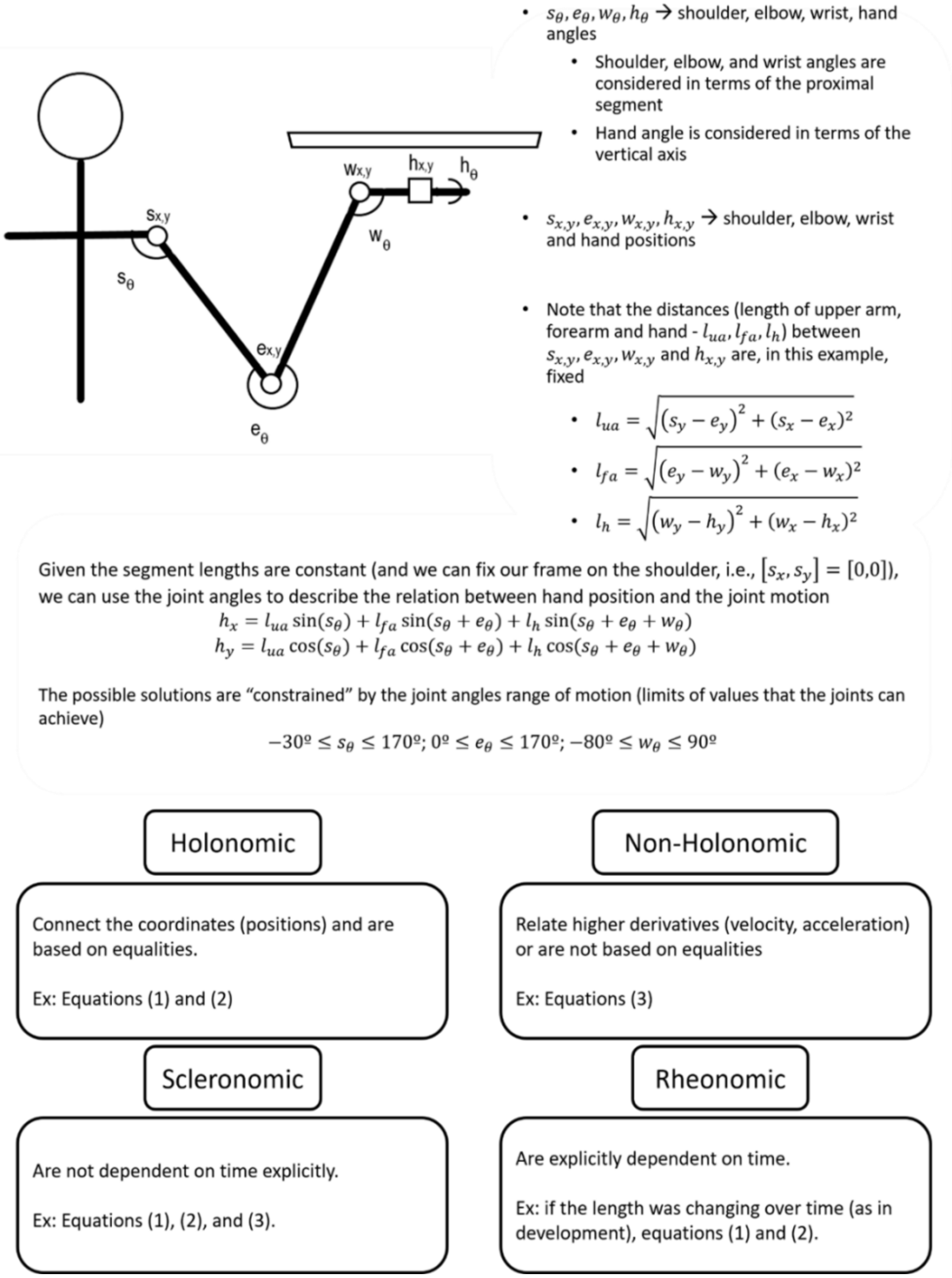
In our "waiter example", the task performance is defined by the following equation of constraint:

$$v = h_y - v_t$$

which states that v (view of the tray) depends on the height of the hand in comparison to a target view (v_t) that would be the best position for the customers to view the contents of the tray. Additionally, the task also encompasses rules such as "do not hit anybody's head" and "maintain the tray orientation at the horizontal". These can be formally stated as

$$h_y > \max(H_y)$$
$$h_\theta = 90^\circ = w_\theta + e_\theta + s_\theta$$

where H_y is the height of all customers' heads in the restaurant, and h_θ is the orientation of the hand as a function of the angles at the shoulder, elbow, and wrist (considering the neutral position of all joints as 0º and flexion as increasing angle value).



- $s_\theta, e_\theta, w_\theta, h_\theta$ → shoulder, elbow, wrist, hand angles
  - Shoulder, elbow, and wrist angles are considered in terms of the proximal segment
  - Hand angle is considered in terms of the vertical axis
- $s_{x,y}, e_{x,y}, w_{x,y}, h_{x,y}$ → shoulder, elbow, wrist and hand positions
- Note that the distances (length of upper arm, forearm and hand - l_{ua}, l_{fa}, l_h) between $s_{x,y}, e_{x,y}, w_{x,y}$ and $h_{x,y}$ are, in this example, fixed
  - $l_{ua} = \sqrt{(s_y - e_y)^2 + (s_x - e_x)^2}$
  - $l_{fa} = \sqrt{(e_y - w_y)^2 + (e_x - w_x)^2}$
  - $l_h = \sqrt{(w_y - h_y)^2 + (w_x - h_x)^2}$

Given the segment lengths are constant (and we can fix our frame on the shoulder, i.e., $[s_x, s_y] = [0,0]$), we can use the joint angles to describe the relation between hand position and the joint motion

$$h_x = l_{ua}\sin(s_\theta) + l_{fa}\sin(s_\theta + e_\theta) + l_h\sin(s_\theta + e_\theta + w_\theta)$$
$$h_y = l_{ua}\cos(s_\theta) + l_{fa}\cos(s_\theta + e_\theta) + l_h\cos(s_\theta + e_\theta + w_\theta)$$

The possible solutions are "constrained" by the joint angles range of motion (limits of values that the joints can achieve)

$$-30º \le s_\theta \le 170º;\ 0º \le e_\theta \le 170º;\ -80º \le w_\theta \le 90º$$

Holonomic

Connect the coordinates (positions) and are based on equalities.

Ex: Equations (1) and (2)

Non-Holonomic

Relate higher derivatives (velocity, acceleration) or are not based on equalities

Ex: Equations (3)

Scleronomic

Are not dependent on time explicitly.

Ex: Equations (1), (2), and (3).

Rheonomic

Are explicitly dependent on time.

Ex: if the length was changing over time (as in development), equations (1) and (2).

Figure 1. Schematic showing the degrees of freedom, the equations of constraint of the waiter example, and the categories of constraints discussed in the text.

These constraints would be former classified as holonomic, non-holonomic and holonomic constraints, respectively. Given h_y is also a function of joint angles (see Figure 1), the task constraints (rules and performance function) would decrease even further the number of functional degrees of freedom of the system. However, although an expert waiter will succeed in the task, there can always be a situation where he/she fails and drops the food on the ground or in a customer's lap. Even when the waiter does not fail to follow the rules (not dropping food), his performance (v) can also vary between the many trips through the restaurant he/she takes during the day. Failures and performance variation are even more probable for a novice waiter. Thus, the fact that the task constraints is not describing how the system *is*, but it is describing what the system is attempting to perform–task constraints do not decrease the number of degrees of freedom nor the range of values that the system's degrees of freedom can take.

Considering organismic and environmental constraints, we can see that, from above, there is a difference between these and task constraints. More specifically, task constraints do not have the same status as those of the environment and organism. Environmental and organismic constraints are always actualized as these are *hard*–they are not followed if and only if the system ceases to be. Muscle-joint relations are maintained as long these muscle-joint relations are still part of the system; force-reaction forces are maintained as long the individuals are interacting in a medium that still exists; tendencies to perceive and act exist and will favor (cooperate) or hinder (compete) with the task requirements [28,33,43].

The task constraints do not constrain the degrees of freedom in the way the equations of the task are described. In fact, task constraints *influence* rather than *characterize* the system. One can even say that this occurs as the task does not constrain the system to a given goal (e.g., error equal zero). Rather, it adds a new variable: the performance (error). It means that, in not actualizing the task constraints described above, for instance, the waiter's performance is evaluated and he/she will avoid performing the task in the same way in the future. In order to solve this issue, we draw on the terms of hard and soft constraints from the literature on constraint programming (see [44]). Hard constraints are the ones that *are* actualized as they are *just* the alternative description of another level of dynamics. Soft constraints are the ones that must be interacted with and, as the individual converges to a (set of) solution(s), *can* be considered as another level of description (see [46,47], for instance). Soft constraints influence the system in terms of a cost/utility function and, over time, dynamically channel the system to the task goal. In this sense, we would categorize task constraints (rules and goals) *soft constraints*. Task constraints capture what perceiving-acting beings *must* be in terms with if there is the intention to be successful in the given task. Only when the system follows these constraints, one can state that the task constraints are actualized in their entirety.

The idea of soft constraints has already been considered in the context of perception and action. Fajen [46,47] (see also [48]) visualized the task constraints as hard constraints and "individual preferences" as soft constraints, given the individual differences' limited influence on the behavior. The idea provided here is qualitatively different as we avoid assumptions on the individual actualizing task constraints–he/she often fails to perform successfully. It is the case that, as individuals improve, they decrease the number of unsuccessful attempts, but the number rarely goes to zero.

It is important to highlight that there is a difference between what constraint programming performs and our application here. In constraint programming, the idea is to set some constraints to facilitate a search algorithm to find *an optimal* solution (see[45]). Here, following Newell's[5] constraints, we are looking to how the movement pattern emerges *from* the system searching for *a* solution[13]. The difference basically lies in the fact that constraint programming is concerned with how to constrain the means to find an *outcome* and we are concerned with explaining the emergent *means* as a constraint on the outcome is imposed on the system.

AGAINST THE TASK-BASED SIMILARITY ASSUMPTION IN MOTOR BEHAVIOR

In a previous work of our group [13], we called the attention for the assumption that a given task condition would be "sufficiently constraining for learning to be of the same kind for all individuals". We criticized this assumption on the basis of the (ubiquitous) presence of task redundancy: there are many solutions to given task goal. Thus, with the areas of motor learning and development being considered, we stated that individuals could diverge in their behavioral response even when attending to the requirements of the same task–which often occurs (see, e.g., [49,50]).

Here, we extend the aforementioned criticism. Above, we implied that individuals–at the end of practice–would be showing the required (or equal) performance in a given task. This is *clearly* not the case for any experiment in motor behavior–which includes the area of motor control. First, even if individuals would reach a target performance, *it takes time (which is different for each individual) for learners to converge to this given target performance*–meaning that task constraints require practice to be actualized (i.e., "make actual, realize" [38]). The variable amounts of time for actualization to occur for each learner means that individuals are influenced by the task constraints differently throughout practice–even if the task constraints are fixed. The fact that humans go through a lifespan process of development and learning – improving performance in a range of tasks – shows that most, if not all, behaviors are accommodating to task constraints over time and their behavior are, over this period, not reflecting the task constraints but the attempt to follow them. Note that this occurs within shorter time scales as well–there is a myriad of terms that relate to an accommodation to the requirements of the task (e.g., "familiarization", "warm-up", "understanding of task requirements").

Second, individuals' behaviors are differentially affected by their performance. That is, *there is individuality in how task constraints drive behavior.* Herbert Simon stated that "…however adaptive the behavior of organisms in learning and choice situations, this adaptiveness falls far short of the ideal of 'maximizing' postulated in economic theory. Evidently, organisms adapt well enough to 'satisfice'; they do not, in general, 'optimize'" [51] (see also [52,53]). Thus, individuals are affected by their view of what is "satisficing" and this view is clearly individual–it depends on what they expect to achieve and their motivation to do so (see [54]). This means that the "cost function" of the task constraints is less *driving* (for behavior) for some individuals than for others.

Third, we are assuming, just for the sake of the explanation, that learners try to attend to tasks constraints (instructions and rules) as they are provided by experimenters (or coaches, therapists). However, in dealing with new requirements (as an individual arrives in a laboratory for an experiment), individuals often need few trials to comprehend what is needed, what is allowed, and, in some cases, must emphasize some aspects of the task before others. In other words, *even when an individual is attempting to perform according to the task constraints (and behavior is observed to change), not all task constraints are considered equally*. In our waiter example, this implies that the waiter might need to focus on maintaining the tray horizontal before caring about the best viewing height. Each has its own time scales (and it dissipates – see [55]).

In summary, task constraints effects differ between individuals in terms of time (when they become actualized) and magnitude (how much they shape behavior) given, at least, psychological aspects (e.g., satisfaction) and initial repertoire.

TASK CONSTRAINTS AS THE TASK SPACE

The idea of a function that influences the system according to the degree of success in achieving the task requirements relates, almost directly, with the idea of a task space (see [13] for a full description). The task space is the function that relates movement (or informational) variables to performance in a given task. That is, a function that describes the performance for a given movement pattern. How such performance (and error) influences change in behavior is dependent on the learner (see the next section). Importantly, such translation of the task constraints in terms of a task space (and as a soft constraint) is consonant with a large body of literature (e.g.,[58–60]).

From our example, the task space is described as the relation of shoulder, elbow, and wrist angles and the height of the tray. Clearly, the task space has a continuous change in error *if* the tray is oriented horizontally; if not, then the error is at the maximum as some food will be spilled on the floor. Figure 2 shows such a task space. *We are aware* that this is not how maintaining food on a tray works (some variation on the horizontal is allowed and some dynamic compensations might occur), but this reduced description is sufficient as an example.

It is important to understand that the translation from task constraints to task space might not be complete. Newell [5] described task constraints as the required implements, the rules, and the goal of a given task. In the present case, we are strongly relying on the rules and goals of the task and setting the topic of implements aside. This is just a matter of simplification for the moment. The implement of a task, for instance the tray of the waiter, is not attached to the body of the waiter and might fall–which would then put it in the same set of considerations made above for rules and goals. However, when being held by the waiter, the way it influences the motions of the body is in line to the description of hard constraints: one does not fail to be constrained by the tray's mass and inertia. However, one can clearly deal with such issue by modeling its influence in a piecewise fashion.

Recent studies [56,57] provide an interesting proposition that relates the task space to affordances. In stating that affordances work as dispositions (what the environment offers to the animal), the task space would be a higher-order property that could be directly perceived. The relation made and implications for theory are beyond the current manuscript (as this seems at odds with our view on affordances) but one can understand the differentiation we are making in types of task spaces (see further in the text) through a different view.

SEARCH AS INTERACTION WITH TASK CONSTRAINTS

Early consideration of perceptual-motor skill learning from the dynamical systems perspective considered the possibility that, when performing actions in a given task, individuals interact *directly* with such space. Newell et al. [14] held that the interaction of the organism with the environment (in a task) would allow perception of the layout of the task space guiding accommodation of the perception-action capabilities of the individual for the new task requirement (see also [61–63]). Such perception would follow similar characteristics as to other modalities of perception as in motion through the space (within or between trials) would allow perception of the topology of the space.

These earlier considerations on the idea of search provided that individuals would demonstrate local and global search strategies, almost as a search algorithm implemented in computer science. For instance, the waiter would perform a gradient descent (evaluating neighboring conditions [similar joint configurations] and following the one with most improvement in performance) and, when stuck in a local-maximum (meaning that there is no other way to improve by small adjustments), the waiter would apply either a large random change (try some new arm position) or follow previous large changes to try to find another (and better) maximum (see [53]).

More recent considerations extended our understanding of how such search could occur [13,64,65]. Importantly, these approaches have encompassed the ideas of initial tendencies of perception-action [28] and individualities on search [65]. Additionally, recent research has demonstrated that how individuals search [50] and find solutions [49,66] limits exploration and adaption to new contexts[67].

Evidence is building to the position that individuals do not search by mimicking search algorithms. It seems that individuals, when searching, do not simply apply *a type of* local search process [68,69]: individuals adapt how they change their movement in terms of how performance changes, accommodating increased inherent movement variability when necessary [69]. Also, the way that individuals change from local to global search (modifying their movement patterns in large jumps to different regions of the task space) seems to be dependent on the performance variability that arises while performing the task [70], which depends on the learner's approach to the task [71], and the task constraints [64].

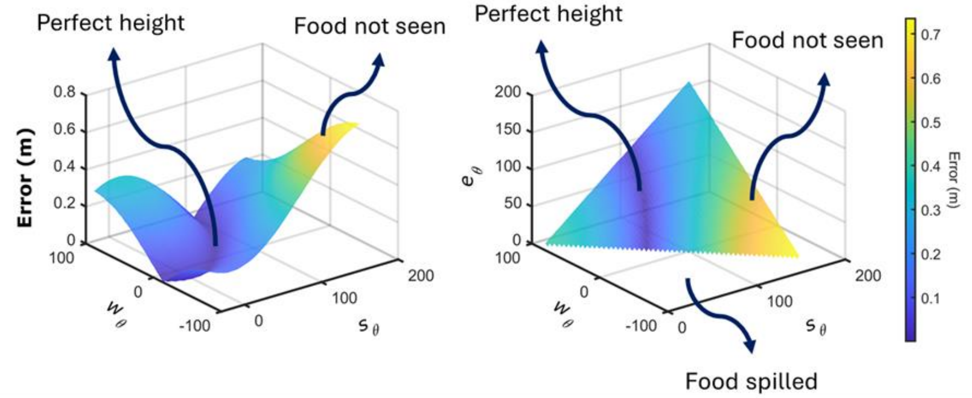


Figure 2. (Left) Task space after constraining $s_\theta+e_\theta+w_\theta = 90^o$: the function of height deviation from the goal (i.e., error: h_y - h_t) in terms of sθ and wθ. (Right) Task space representing the rule $s_\theta+e_\theta+w_\theta = 90^o$ (horizontally oriented tray) and, within the plane (allowed by the rule), the error.

Individuals do not seem to be freely able to search into *any* movement possibility region. They are largely constrained by their intrinsic tendencies of action (the perceptual-motor workspace, see [13])–their stabilized movement patterns [65,69,72]–which they adapt as a whole to accommodate the task requirements [73,74]. This process of search has also been illustrated in terms of the attention to informational variables [39,75,76]. Perceptual learning (i.e., attending to more useful informational variables) shows similar dependence on constraints [77] and individuality [40,78].

To update our example, then, each waiter that we would like to train to work in our restaurant would start and search differently through the movement possibilities. This could occur given inherent structural differences between them (e.g., one is taller than the other), functional differences (e.g., one is weaker than the other and he/she needs to work in terms of a less fatiguing position), and, also, they could work in terms of different perception action cycles (e.g., one visually tracks the height of the tray and adjusts it accordingly while the other prefers to try to fix the position of the tray while compensating joint motions in terms of proprioception and haptic information). These differences elicit different ways of searching during the task by, first, finding solutions to maintain the tray in a horizontal orientation and, later, exploring how to increase orders from customers to find the best view of the tray (*v*).

Note that, during this search, if one individual is weaker, some solutions, requiring large forces (arm and forearm parallel to the ground) could lead to fatigue and increase variability at the tray. As variability is high, individuals could not differentiate whether changes in performance occur because of their search or the inherent variability of the body (see [78]). Thus, either individuals avoid that region as a whole [70] or they search differently as to gather information of the task space [69].

If the task is overly constraining individuals might converge to similar solutions even when they started in different initial conditions [27]. For instance, let us say that we add the requirement for the waiter to walk around with the tray for long periods before resting. In this situation, even stronger individuals move towards more efficient solutions as to be able to cope with long periods holding the tray. Thus, it is possible that the weak and strong individuals converge to a single solution. Note that, if the task is not as constraining as it could be, individuals can diverge largely given their initial differences, distinct search strategies, and the fact that the task allows multiple responses (see [49] for a discussion on the topic). In fact, even when the task is overly constraining, it seems that individuals might diverge in how they error [79] converge in given aspects and vary in others (similar means and different ends) [80].

The process of search in the acquisition of perceptual-motor skills is a contemporary research focus [13,65,70]. However, despite the many unknowns in this process of search, there is evidence that individuals do search to interact and actualize task constraints. That is, the aforementioned research has demonstrated that task constraints can be considered as soft constraints that, over practice, individuals perceive and act accordingly, modifying attended informational variables and action parameters.

DIFFERENTIATING EXPERIMENTER-FRAMED AND LEARNER-FRAMED TASK SPACES

It is tempting to directly employ the function relating performance and movement possibilities to characterize the task space on which individuals are searching – as usually it is done. However, the typically constructed task space (e.g.,[60,71,81]) might not represent what is actually searched on. This general task space is an experimenter-framed function that is bounded in terms of the task rules and with some function relating performance to movement parameters, from the best possible performance (e.g., zero error) to the worst. This can be derived without any knowledge about the individual.

However, it is common to see that individuals differ largely in how they change given the same outcome of the task. That is, they adapt differently in a trial-to-trial basis [82,83], to different task conditions [69], which inevitably leads to a different task performance at the end of the practice. Experiments have shown that the interaction between the individual and task space (mediated by the environment) creates a more dynamic and individualized task space [27,70,71,84]. This can be framed as a learner-framed task space that includes, beyond the relation of performance and movement, expectations (individually, socially, culturally driven) and others context factors. This has already been pointed out by Reed and Bril [30] considering the proximal environment of the being and more generally by Broffenbrenner [85]. Using the "waiter example", it is one thing for a child, pretending to be a waiter, not to be able to maintain the tray horizontally oriented with his toys falling without consequence, and another for a waiter of a renowned restaurant to fail to follow such a rule, potentially dropping food on restaurant-goers. In the same sense, it is one thing to have 10% of errors in throwing a dart into a board for an individual trying to beat his friends in a bar, and another for an athlete competing in a darts championship (see [10] for more on how "social" aspect of task constraints can be considered).

The important point is that experimenter-framed and learner-framed task spaces can differ qualitatively, and this has considerable impact on what is being studied (see Figure 3). Clearly, if these other factors do not interfere with what individuals are attempting to achieve (in line to [48]), both learning and practice leads to convergence of the learner-framed task space to the experimenter-framed task space. However, if the other factors do interfere with what the individual is attempting to do (and to a similar degree as performance outcome itself), then we must include these extra factors to understand how search occurs in the way it does and, consequently, why behavior changes the way it does.

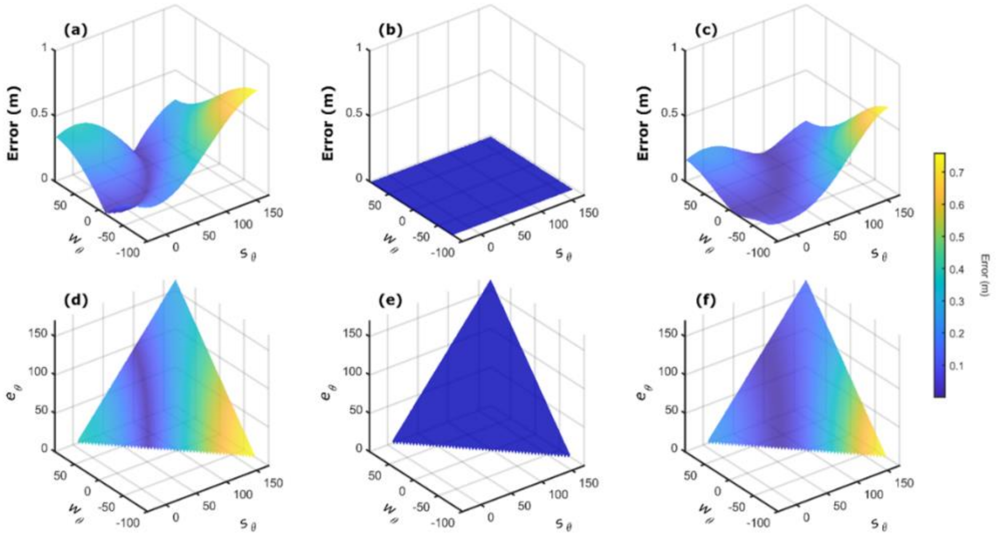


Figure 3. Task spaces considering three different situations. (a) and (d) show the task space and task space + rule (with the horizontally orientation of the tray rule) when only performance matters. (b) and (e) show the task space and task space + rule when only the rule is applied. That is, the waiter only needs to maintain the tray horizontally oriented. (c) and (f) show the task space and task space + rule when individuals do not need to achieve the best height–only a good performance suffices. (a) and (d) is usually what experimenters would consider and the example of the experimenter-framed task space. All other situations exemplify possible learner-framed task spaces. For instance, (b) and (e) could refer to novices that were, at the moment, instructed to try only to maintain the tray horizontally, without caring much about the height. (c) and (f) can refer to the situation described in the text where no one ever achieved maximum performance and, thus, the waiter is only trying to achieve performances close to the group average–a socially imposed expectation on performance.

The idea of a learner-framed task space follows similar lines to how the environment is considered in Ecological Psychology. Individuals would not perceive the environment in terms of physical measures and units (e.g., length in meters, mass in kilograms) but would perceive in terms of its body-scale and action possibilities [47,86] – i.e., affordances [86]. *Climbability* of a stair (i.e., the perception of the stair being climbable), for instance, would be perceived in terms of biomechanical characteristics of the individual [7] and his/her functional capacities [87]. The learner-framed task space encompasses how the individuals perceive the requirements of the task space, not only grasping the biomechanical or functional variables but also individuals' and context' expectations.

It is important to note that although the learner-framed task space is not as "objective" as the experimenter-framed task space is, it is amenable for empirical manipulation. Inducing competitive context or informing individuals of others' performance (in terms of normative feedback or best-score-so-far in a given task) can clearly modify how individuals understand what the task expectations are and the need for different search patterns. In Pacheco et al. [70], two groups performed in different task spaces on which local minima were either "close" or "far" from the stated best score. Non-local search patterns emerged primarily from those who were in the "far" condition as they perceived that the given solution would not lead to the expected result. For most individuals in the "close" group, nevertheless, because of their proximity to the best performance in these local minima, they never modified their search patterns and failed to achieve the goal. In addition, we can think of the learner-framed task space as the resulting potential function that emerges from the interaction of all three constraints (task, organism and environment). It might be possible, then, to measure how the strength of the potential at a specific region of the task space differs between individuals (see more in the Implications section).

ACTUALIZING CONSTRAINTS

An issue that one cannot overlook is the fact that although task constraints can be considered as soft constraints, they become, over practice, more and more "encompassed by" the emergent coordination of the learner. That is, through practice, task constraints–the layout of the task space–are becoming actualized in the perception-action coupling. This, naturally, leads to improved performance in the task and relatively permanent changes in how one performs the activity in the given context–i.e., individuals have learned the skill.

We agree with Shaw and Alley [88] when they describe that "learning is a lawful operation that increases the coordination between perception and action series. Metaphorically, learning is a function that tightens the constraints on the double helix, bringing the perceptual 'helix' (or series) into closer alignment with the action 'helix' (or series)" and further "Roughly speaking, perception is a mapping from the series of values taken by the environmental variable into the series of values taken by the organism variable, whereas action consists of the inverse mapping. There is, however, a special relationship between the perceptual function and the action function that guarantees their covariation whenever the organism is successfully guided by perception through a series of felicitous regulatory acts (e.g., muscular adjustments) that achieve an intended goal (e.g., the grasping of an object). Under such felicitous circumstances, the two functions must become duals so that the course of values assumed by one constrains the course of values assumed by the other […] in an ongoing and mutual process".

The process just described of increasing coordination in the mappings between perception and action (i.e., learning) is, for us, a result of the interaction of the individual with the task space: a response to continuous interaction with the soft constraints of the task. The task does not constrain emergent perception-action coupling into a single solution, as task constraints are usually redundant and afford degeneracy, but it guides change (through a search process) for an increased coordination between perception and action [88]. As task guides change, the constraints become part of the perception-action coupling. That is, as individuals search, attending to more useful informational variables [39] and modifying actions accordingly [13], the individuals' emergent action actualizes the task constraints.

It is important to clarify that "actualizing" task constraints is not synonymous with learning despite learning being the path for "actualization" to occur. That is, one does not need to actualize task constraints for learning to be inferred. Changes in movement behavior–relatively permanent ones [89] (which would refer to the original definition of motor learning)–occur given the discovery of stable perception-action solutions (equilibrium regions in the perceptual-motor workspace [13,14]). Such stable solutions might still be far from performing at the best possible at a task and, thus, are not actualizing task constraints.

IMPLICATIONS OF TASK CONSTRAINTS AS SOFT CONSTRAINTS

Considering the idea that task constraints are soft constraints has direct and indirect implications for the understanding of motor behavior. These implications, therefore, should modify how interpretation and design of experiments are conducted, and how principles of motor learning are applied to practice.

TASK CONSTRAINTS TAKE TIME TO BE INCORPORATED IN THE PERCEPTION-ACTION CYCLE

Following the task-based similarity assumption, a number of studies rely on task manipulations to demonstrate either changes of behavior or consistency in a given aspect of behavior. The idea is that if the same aspect of behavior is present in the full range of task manipulations, one has a reason to infer that this given aspect is general. Thus, one can infer that the consistent aspect being observed is a principle or basis for motor behavior.

If the task constraints are *soft*, then time (practice) must be allowed to have task effects observed in behavior. Usually, nevertheless, not many practice trials are allowed, and this might actually limit the effect of task constraints. As search is required for individuals to allow task constraints to drive behavior and decreasing the number of trials would decrease the possible change to be observed between tasks. Conversely, many studies investigating the impact of experimentally manipulating task constraints are often done in sports contexts with participants that already play the sport. This situation does not allow us to see the full learning and search process.

Moreover, it is conceivable that, when individuals know only a few trials will be available, search is avoided to maintain task performance to a sufficient level (a "satisficing" performance). Thus, it could be that consistency in given parameters is nothing more than *the simplest* solution for that given context is being maintained for all conditions–which would be in line to the traditional idea of generalization between tasks [90,91].

TYPES OF TASK CONSTRAINTS

Without being exhaustive, there are many subtypes of task spaces that should be considered when evaluating how individuals search and accommodate task constraints. There are tasks that are dichotomous (e.g., jump from one side of the cliff to the other) while others are continuous (e.g., jump as far as possible). For the latter, we would expect an exploration of different means to reach the maximum of that task without much concern if one trial resulted in short distance. The former creates a situation where an individual would converge to solutions that attend the minimum distance (largely constraining the search process) but would not be channeled to solutions that increase the distance much further beyond what is required–as this is totally unnecessary.

On the same idea, there are tasks that require the maximum of some capacity and others that require precision. Still on the example of jumping as far as possible, this requires individuals to find *a* solution that maximizes jumping distance. We are not aware of any study that defined that individuals have *a* single solution maximizing these types of task (see [92,93]) but individuals might constrain search as finding another good solution might be time consuming. A task requiring precision, for example, is jumping to a given distance. If the distance does not approach the individuals' maximum, individuals can explore a diversity of movement solutions that lead to the same goal. Thus, search is clearly beneficial and large divergence might occur between individuals.

Finally, there are tasks in which errors *will* occur; in part, the task was designed for it. Speed-accuracy trade-off designs require individuals to either minimize movement time while maintaining spatial accuracy [94] or match a movement time attempting to be as spatially accurate as possible [95]. In the matching type of task, individuals *will* miss the target in some (if not all) trials as the required movement time is too small for corrections to occur (see [96] and responses for an overview on the theme). In this type of task, given that the goal is "virtually" impossible, individuals might choose which type of errors matter more given they vary in terms of bias on the target and variability in both space and time (they can miss the movement time requirement) (see [79,97]). The search in this type of tasks, then, is to improve in their own prioritized error measure–which is clearly individual.

SEARCH MIGHT INVOLVE VARIABLES NOT ENCOMPASSED BY THE TASK SPACE

Usually, there are several degrees of freedom related to a given task performance. An individual needs to explore and, in interaction to the task, find dimensions that are relevant, or not, to the task at hand. Throughout the learning process, then, exploration might occur in dimensions not directly related to performance. Following our example, if the waiter varies the position of the tray horizontally, it does not affect the performance, but, if this is not known, some trials are necessary for him/her to perceive the height of the tray as the main variable. Note that this only occurs given the task constraints are soft and, therefore, need not be actualized. If the individual can search in terms of variables irrelevant to the task, the researcher, if wanting to understand skill acquisition, should consider how (and if) the individual *finds* variables that are relevant to the task. More importantly, the external observer should not assume a set of variables at first.

There are two reasons for this. The first, as stated, is to understand how individuals, through search, find ways to improve their performance. There is evidence that in some cases individuals do not always find the most relevant variables in a task depending on his/her search pattern [71]. Thus, assuming *a priori* a specific set of movement parameters that would change through learning might be misleading. For instance, Beek and van Santvoord [98] postulated that, in knowing how an expert performs, one could see how learners converge to this "expert" way of behaving. By using mathematical formulas that describe how experts do and can modulate juggling, they studied novices in the same task. Clearly, such an approach already eliminates individuals at the first stage of learning juggling (before they can maintain juggling for some period of time) (see [99]). But, more important, it assumes that individuals will search or act in the task in terms of the same variables as the experts–which might not be the case. Also, in understanding that there are many dimensions that one could improve that researchers and coaches are not aware (not because of negligence, but because it might be impossible to know it all), one should avoid approaching any behavior based on the "champions' model" as in providing a direct model of how to behave might limit exploration in dimensions not considered by this given model.

This is true for other classical movement paradigms. For instance, in the bimanual finger coordination paradigm [33,100], learning new relative phases between fingers' motion has been studied in terms of the relative-phases that individuals would try to maintain (e.g., [29,43,101])–probably, because this is directly specified in the model. However, developmental [72] and learning studies [65] have shown that very few individuals work in terms of relative phase *only*. For instance, in Brake and Pacheco [72], found frequency of oscillation, movement amplitude and other aspects of the task were broadly explored being, in some cases, properly modulated to afford consistent performance in the anti-phase movement pattern between arms.

Another reason why one should not limit observation to relevant parameters of the task is that it has been continuously shown that individuals take advantage of "irrelevant" dimensions in performing a range of tasks (see [102]). It has been postulated that the usage of irrelevant dimensions is a sign of flexibility of the system [103] or how the system stabilizes a given important variable [104]. The logic behind such argument is simple: if the waiter knows how to maintain the tray at the given height (and horizontally oriented) in many ways, then he/she can maintain the performance adapting to many perturbations along the way. This is because the system is abundant [105–107] and the consideration of these extra variables might explain why learners modify their demonstrated abundance over time (see [108]). Thus, in considering how individuals attend to the task constraints, it would also be important to understand how they attend to what *was not* constrained (see [109]).

We should also remember that there are variables that extend what one considers as the task. From our example of the waiter, if the tray becomes hotter as time passes with food above it, it might be that individuals modify the way they hold the tray, the time they can move with it, or, even, if they hold with both hands. That is, even though tray temperature is not explicit in the task constraints, it does alter how individuals perform the task. Another instance, it is thought that, at first, the Fosbury Flop jump was "accidentally" performed and this led to improved performance in the high jump compared to, at the time, traditional straddle technique, Western Roll, Eastern cut-off or scissors jump. As Fosbury stated himself: "When I got into high school, my coach tried to teach me how to do the straddle. Because he said the scissors [technique] that I had been using was not good enough for me to keep up. We started to work on it, he coached me, and I was awful. Terrible. We got through most of the season with poor results and I asked if I could go back to the scissors. He relented and said yes. It opened the door for me and the next meet I started scissoring. I didn't have a plan, but as the bar was raised higher, I changed my body position to adapt to the higher bar–from sitting over the bar in the scissors to a back layout lying flat on my back. And I improved half a foot in that first meet that I changed. I scored a point for the team and that was my breakthrough revolutionary moment"[110]. An issue, however, that highly favored the usage of the new jump was the landing surface that was modified from sandpits to foam matting. That is, hardly anyone would attempt the Fosbury Flop (that uses the back to landing) if an injury is likely.

In line with these ideas, Baggs et al. [111] state that much of the context, including environment, implements, and others, might *enable* individuals to learn a range of behaviors. They provide the examples of infants standing upright and walking describing that through exploring possible "helpers" (furniture, caregivers, etc.) individuals are able to experience standing and, as they experience possibilities, learn to not need the helpers in any case. They call these helpers as enabling constraints. Note that these (e.g., furniture) are also the enabling constraints of the first steps–in infant cruising–that would support later walking.

Finally, in understanding that there are some variables of the task space that are *beyond* what we usually consider, there are some that we consider as being part of the task space that should not be. In following the line of walking discussed, one could consider as fact that toddlers would attempt to perform walking in ways as to avoid falling (an emphasis on "stability", see [112]). Thus, the task constraints would be discussed in terms of maintaining the center of mass above the base of support, consider dynamic balance variables and so on. However, falling seems to be common while learning how to walk [113]. Toddlers fall every now and then (17 times per hour!) and this does not seem to limit them in trying. In fact, Snapp-Childs and Corbetta [114] have demonstrated that there are children that use a strategy that takes advantage of initially falling to move forward. Thus, variables (and strategies) that one could assume as being avoided–or not manipulated by the individual–might be actually allowing the desired behavior to occur.

CAN PRINCIPLES OF MOTOR CONTROL AND LEARNING BE EXPLAINED BY TASK CONSTRAINTS?

A common assumption in the motor control domain is that of specific variables being optimized (see [115] for a review) and that these variables, then, are representative of principles of control. Usually, this is postulated through a cost function that is optimized and validated against a range of task manipulations.

Nonetheless, it is important to consider whether the task constraints are not *the* "force" driving consistency in such aspect of the movement (the principle being postulated). Pacheco et al. [13] have described, for example, how many aspects identified studying task space variability (e.g., the Uncontrolled Manifold [59,104], or Tolerance [60]) might be, rather than general principles of control instantiated from the central nervous system, just emergent aspects arising from interactions of the individual with the task constraints (see also [116]). A stronger case, the idea of decreasing noise (variability in the end-point), was derived observing hand reaching experiments and eye movements [117]– both situations in which less variability *is* desirable for the task. If that is the case, one cannot know whether there is a cost function being implemented in the central nervous system (or wherever) that aims to decrease end-point variability or if it is just an aspect that falls out from searching in the task space of a task that requires low variability.

Truly, we need to make justice to Harris & Wolpert [117] – authors who proposed a view on "optimizing" variability. That is, they claimed that there would be no need for an optimization algorithm as individuals would learn the most appropriate response: "Moreover, there is no need for the central nervous system to construct highly derived signals to estimate the cost to the movement, which is now variance of the final position or the consequences of this inaccuracy, such as the time spent in making corrective movements. Such costs are directly available to the nervous system and the optimal trajectory could be learnt from the experience of repeated movements." This is in line to our view but restricted to tasks that require accuracy at the end-point.

THERE IS NO NEED FOR OPTIMALITY IF THE TASK DOES NOT DEPEND ON IT

As we considered earlier, the types of task spaces clearly influence what is satisficing (using Simon's term) as some errors (poor performance) are not as problematic as others. But there are other considerations that must be done. In our example of the waiter, let us say that the maximum number of individuals ordering food per turn of the waiter in the restaurant is 30 and this is proportional to our v variable. If the maximum ever achieved (or the great majority of individuals achieve) was around 20 persons, then, no new waiter will be driven to reach 30. First, it is necessary for one to know what is the maximum that *can* be achieved–if nobody ever reached 30, how can one know that is possible to achieve it and modify behavior to do it? Second, even knowing the maximum, if the social context accepts 20 as a good number, searching for solutions beyond that might even result in worse results in the long run as searching might result in performing bad solutions here and there (the exploration/exploitation dilema [118]) (see Figure 3).

In fact, current considerations in motor learning highly emphasize the need to understand social and individual aspects in modulating motivation in learning [119–121]. A recent model summarizes the idea through the concepts of self-efficacy (how one sees its own capacity to perform) and believed satisfactory performance (what is the "score" believed to refer to "good" performance) and how they interact with trial-to-trial corrections [122–124]. From this model, individuals that are performing *beyond* what they believe to be a good performance, stop attempting to improve up to the moment they "update" what is believed to be good. Additionally, how much one attempts to correct is also modulated by the individuals' self-efficacy (see also [125]).

UNDERSTANDING AUGMENTED INFORMATION AND STRUCTURE OF PRACTICE

A point that must be reconsidered when encompassing the idea of soft constraints and search is how augmented information and structure of practice affect motor learning. Much of the work in this area relates to the traditional information-processing point of view (see [89]) and this must be clearly revisited in the current context.

Pacheco et al. [13] (see also [12,126]) provided a number of considerations in terms of how augmented information and other aspects of practice might modulate search-strategies. Note, however, that this requires a more elaborated deliberation if task constraints act as soft constraints. For instance, we postulated that initial interaction with different task constraints might be similar as individuals have not had enough practice to accommodate the differences between these task spaces. However, in some cases, small changes in instructions[127], demonstrations [128] or just focus of attention [129] can significantly modify the behavioral outcome.

A better understanding of these aspects of practice will emerge when one is able to classify how these aspects modify the interaction of the individual with the task space. As argued in Pacheco et al.[13], demonstrations might constrain the area of the task space at which the individual is performing, but it might also lead to an internal focus of attention modifying the variables that individuals initially interact with and, in this case, constraining how and if interaction of the task space occurs. For instance, if a demonstration of a waiter leads to novices attempting to reproduce a given joint position demonstrated, their focus will be on their own movements deviating from that given joint position. This limits the interaction of the individual with the actual task space (task relevant variables) and, inevitably, there is no way on which performance (errors) can drive him to modify his behavior.

Another issue, that has only recently considered by our group (Santos, C. C. A. 2024. Focus of attention as constraints on the perceptual-motor workspace. *Master Thesis.* University of São Paulo. *[In Portuguese]*), is that task manipulations, depending on which ones we are describing, might have their own dynamics. In Pacheco et al.[13], two types of manipulations were considered: ones that modify the search space (e.g., instructions, demonstrations) and ones that modify the search itself (e.g., feedback, practice schedule). While the latter cannot be avoided–as the manipulation is maintained through practice (see [130])–, the impact of an instruction, nonetheless, can "dissipate" over time. Considering search as this interactive process between individual and task demands, an instruction is constraining (softly) the space of possibilities that the learner should search on (e.g., "try to release the ball when the forearm is perpendicular to the ground"). Depending on the continuous interaction with the task space (i.e., the outcomes over time), such an initial instruction might have its effect dissipated over time.

HOW SHOULD COACHES APPLY SOFT CONSTRAINTS IN TRAINING?

Interestingly, examples of the application of principles derived from ecological psychology and dynamics systems theory have already begun hinting at the notion of soft constraints, timescales to actualize the task space, and experimenter vs learner frames of reference. Diverging from our waiter example, in baseball, Gray and Sullivan [131] argue the need to present batters with opportunities during practice to pick-up specifying information about the trajectory of the pitch and channel the dynamics of the hitting motion. In-game situations, batters are confronted with several intentions when coming to the plate: down by one run-try to hit a home run, runner on third-just get on base, hit to opposite field, etc. However, in practice it is always one intention, hit hard. With different intentions comes timing and swing mechanics, and provided batters need to modify their perception-action cycle to more relevant information it is emphasized that "such changes in information movement control require practice to get good at!".

Clearly, we see how the interaction between information variables and individual intentions can reframe the task space between practice and game conditions and acknowledge time/practice requirements. What is incongruent with the notion of soft constraints and current practical recommendations is assuming all learners *will* converge on the same informational variables if they are provided with the same instructional constraints. This presents the same issue of task-based similarity assumption discussed above. In general coaches are recommended to promote external focus of attention and actively encourage learners to avoid altogether internal focus. Yet survey-based results revealed that coaches and athletes primarily utilize internal focus, but athletes focus of attention varies by sport, practice, and competition [132,133]. Moreover, some evidence suggests expert swimmers can switch between internal and external without performance loss [134]. Understanding that search can occur on variables not encompassed by the task space (see above), it is relevant to consider that coaches may need to be more strategically, on a learner-by-learner basis, about what instructions to give that channel accommodation of the task space (see [135]).

FINAL COMMENTS

In summary, in this manuscript we proposed that, considering the categories proposed by Newell [5], task constraints are different than environmental and organismic constraints given their ontological status. We showed that the environmental and organismic constraints seem to be more in line to the concept of hard constraints while task constraints reflect soft constraints. This differentiation provided consequences in how task constraints must be framed (in terms of the learner and experimenter) and for interpreting results in motor behavior. We clearly cannot exhaust implications of this advancement, but it is our hope that this can support new insights in the area.

There are a variety of ways on which the present ideas can be further encompassed in the literature. In connecting task constraints to how individuals interact with the current context and how these are modified over time, we are helping to better structure the ideas of constraints, perception and action, and change. For instance, task spaces have been considered as the interface between what the task requires (and environment affords) and individuals capabilities [73] or, in other words, means to understand the concept of affordances (see for a view [56,57]). It is our understanding that the "unique" matching between perception and action as postulated by Shaw and Alley [88], the "incorporation" of task constraints, corresponds to the clear relation between what the environment invites a given organism to perform and the organism's capabilities.

These ideas would help to explain interesting relations that occur during development. For instance, novice toddlers see and differentially explore large gaps, but still try to walk through it (see [136]). Toddlers perceive non-passable gaps as passable (in affordance terms). As the "passing" task constraints are soft, failure is allowed: this just means that toddlers still did not attend to more useful information to perform such a task and might have not modified actions accordingly.

Finally, the idea of incorporating constraints might also be helpful in explaining "on the fly" adaptations to perturbations. Provided experience will allow individuals to move in a task in terms of task space (relevant and irrelevant) variables, unexpected perturbations might lead to new forms of adaptation given coordination between perception and action already span these. It would also explain how perturbations help to induce learning of adaptations. Many dimensions of adaptive behavior might be learned through new perturbations–new dimensions of the task space are "discovered". The perception-action solution becomes more stable against a larger range of perturbations–specifying different responses to different things.

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