ARTICLE

Rationality in Human Movement

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O'BRIEN, M.K. and A.A. AHMED. Rationality in human movement. *Exerc. Sport Sci. Rev.*, Vol. 44, No. 1, pp. 20–28, 2016. *It long has been appreciated that humans behave irrationally in economic decisions under risk: they fail to objectively consider uncertainty, costs, and rewards and instead exhibit risk-seeking or risk-averse behavior. We hypothesize that poor estimates of motor variability (influenced by motor task) and distorted probability weighting (influenced by relevant emotional processes) contribute to characteristic irrationality in human movement decisions.* **Key Words:** sensorimotor control, decision making, risk, neuroeconomics, prospect theory

INTRODUCTION

Movement is an essential component of our lives, making it possible to interact with the world around us. Consciously or subconsciously, our brains are constantly making decisions about how to move our bodies through space, and individuals often exhibit preferences when executing certain movements (*i.e.*, preferred walking speed).

It is acknowledged widely that humans often are irrational when making *economic* decisions under risk. That is, they do not objectively consider uncertainty, costs, and rewards in the context of money or commodities, causing them to exhibit risk-averse or risk-seeking behavior (28). For instance, most people would choose to receive a small but certain monetary reward over a larger uncertain reward, which is indicative of risk aversion. An ongoing question in the field of motor control is whether humans make rational or irrational *movement* decisions. Rational movement decisions would be reflected by objectively or appropriately accounting for one's motor variability and the inherent costs and rewards associated with a movement strategy. As an example, imagine that you are walking along the edge of a curb. Given that there is some mediolateral variability in your foot placement, how close can you get to the edge without stepping off the curb? If you were highly variable in your foot placement, a rational decision would be to leave more distance between your feet and the edge, minimizing the chance that you step off the curb. In contrast, having high variability and confidently walking directly along the edge in a risk-seeking manner (or having low variability and fearfully keeping a substantial distance from the edge in a risk-averse manner) would evidence irrational behavior. Importantly, we would expect your behavior to change with potential movement outcomes. If you were walking along the edge of a cliff rather than the edge of a curb, you are rewarded with a beautiful view near the cliff edge, but the consequences of a fall are much more dire, and you likely would use a more cautious strategy than at the curb edge. Because of potentially damaging consequences of poor movement decisions, characterizing and predicting irrationality have valuable implications for injury prevention and treatment. By pinpointing irrational movements in an individual, population, or environment, we can design intervention strategies to encourage appropriate movement behavior.

Understanding movement behavior under risk is particularly relevant in the context of aging and clinical populations. Generally, older adults performing a goal-directed movement task exhibit a limited range of motion and greater movement variability (7,21). In addition, both older adults and patients with Parkinson's disease take longer to complete a movement and manifest deficits in their postural control when compared with a younger or healthy population (3,9,13,31). However, it seems that movement strategies in both patients and healthy adults cannot be explained by biomechanics alone (12,13,18,25). Considering movement as a decision-making process suggests that psychological factors also may contribute to the movement patterns of older and clinical populations. In this case, the seemingly impaired movements of these groups may reflect a conscious or subconscious decision based on altered valuation/perception of the movement outcomes or probability of the outcomes.

In this article we present work aimed at classifying movement behavior as innately rational or irrational. We believe that a neuroeconomic framework is particularly apt for assessing

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Accepted for publication: September 10, 2015.
Associate Editor: Roger M. Enoka, Ph.D.

0091-6331/4401/20–28
Exercise and Sport Sciences Reviews
DOI: 10.1249/JES.0000000000000066

rationality in movement. Through a series of sensorimotor decision-making studies, we have found that healthy young adults exhibit a number of irrationalities in movement, including risk-seeking tendencies in arm-reaching (ARM) and whole-body movements with explicit end point costs, as well as distorted weightings of probability in the presence of postural threat that is salient to a movement. These findings are summarized in Figure 1.

We now elaborate on movement as a decision-making process and then describe various movement studies and their contributions to our overall hypothesis that poor estimates of motor variability (influenced by motor task) and distorted probability weighting (influenced by relevant emotional processes) contribute to characteristic irrationality in human movement decisions.

MOVEMENT IS DECISION MAKING UNDER RISK

Movement is an extremely complex biomechanical and neuromechanical process. This complexity stems, in part, from a high level of system redundancy. There seemingly are infinite combinations of trajectories, limb configurations, and muscle activation patterns that can accomplish even simple movement goals. Such redundancy indicates that the brain must make a number of choices concerning how to execute a movement. In this way, we can see that every movement represents a series of decisions — more specifically, decisions under risk.

We define *risk* as variance in the outcome of an action. This refers to the spread of possible outcomes wherein a bigger spread represents more risk. Risk affects many of the choices we make but is demonstrated easily using a financial example. Consider a choice between (A) a sure bet of winning \$5 and (B) a 50:50 chance of winning either \$0 or \$10. This is a decision under risk because there is more than one possible outcome. The expected value of each scenario is computed by summing the product of their possible outcomes and the associated probabilities: $E[V] = \Sigma pX$.

$$E[V_A] = \sum p_A X_A = (1.0)(\$5) = \$5$$

$$E[V_B] = \sum p_B X_B = (0.5)(\$0) + (0.5)(\$10) = \$5$$

Because both options have the same expected value (mean winnings), a rational individual would see these options as equivalent and have no driven preference between the two options; we consider rational behavior synonymous with having a *risk-neutral* attitude, meaning their decisions are not swayed by the presence of risk. However, people tend to be sensitive to risk in economic decisions, having a clear preference for option A or option B. *Risk-averse* individuals tend to prefer a lower certain reward over a higher uncertain reward, and they would choose the sure bet (option A). *Risk-seeking* individuals, on the other hand, are attracted to the possibility of winning a high reward over a lower uncertain reward, so they would choose the gamble (option B). These are manifestations of irrational behavior.

Note that, when using the above definition, two factors contribute to the amount of risk in a given decision: outcome value and outcome probability. Moreover, we can quantify the amount of risk (variance) in a financial lottery using these two factors. For a lottery with a probability p of winning a reward X against a zero-outcome alternative:

$$\text{Var}[\text{lottery}(\$X, p)] = pX^2(1-p) \qquad (1)$$

Lottery risk increases quadratically with reward and with probabilities approaching 0.50. In our example, the risk associated

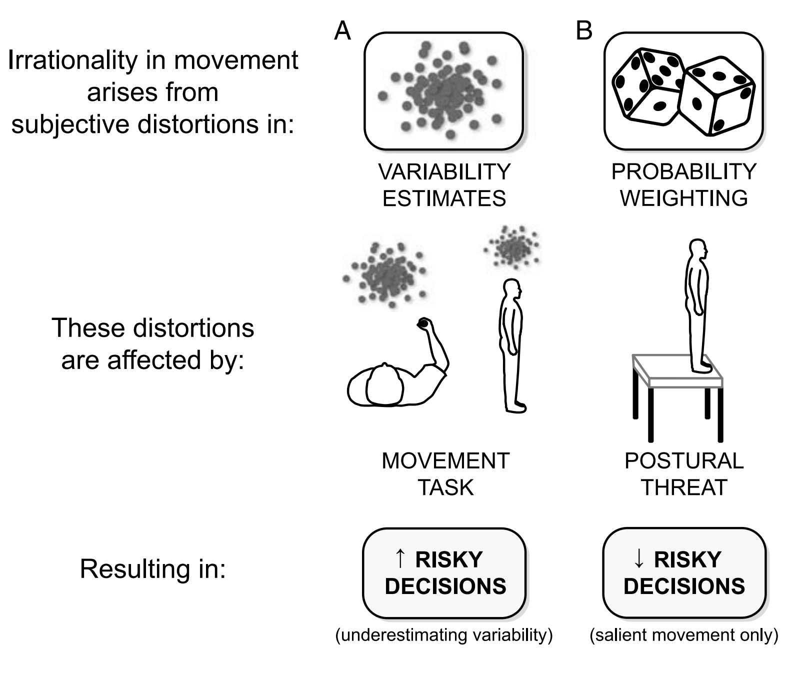

Figure 1. Summary of irrationalities in movement decision making. Irrationalities in movement arise from distortions in (A) estimates of motor variability, which may change with motor task and increase the number of risky decisions for underestimations of variability, and (B) probability weighting, which becomes more distorted with postural threat and decreases risky decisions for a salient movement.

with each lottery is Var[A] = 0 and Var[B] = \$25, making option B the riskier choice. The relative contributions of value and probability to the riskiness of a lottery with a probability p of winning a reward X (against a zero-outcome alternative) are illustrated in Figure 2.

The formulations of risk we have described so far also translate to the movement domain. Risk arises in motor control because our movements are inherently variable. That is, it is unlikely that we can make exactly the same movement twice. Consider that when making repeated movements (*i.e.*, pointing to a target with your index finger 100 times), there is variability in such characteristics as end point position, peak velocity, and acceleration profile. Movement variability emanates from noise in perception, planning, and execution of a movement, as well as from noise in the encoding and transmission of neural signals (6,29,30). Overlaying the economic ideas presented above, the amount of risk in a movement also is determined by the potential outcomes (*i.e.*, unsuccessful or successful movements) and the probability of those outcomes (which depends on motor variability).

IDENTIFYING MOVEMENT DECISIONS AS RATIONAL OR IRRATIONAL

Now, with a foundation for assessing movement risk, how is motor behavior classified as rational or irrational in the presence of this risk? Because of the variability in our movements, a statistical framework is often used to develop models for explaining or predicting movement under risk. These models may be normative (identifying the rational or optimal decision) or descriptive (determining what decision someone would actually make regardless of whether it is rational/optimal or not). Comparing actual movement behavior with predicted behavior from these models provides insight to the rationality of movement decisions.

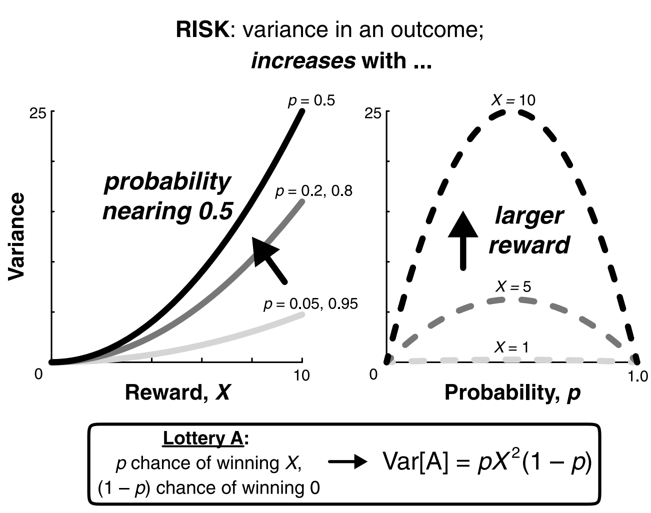

Figure 2. Risk is affected by outcome value and outcome probability. The relative contributions of value and probability to the riskiness of a sample lottery A with a probability p of winning a reward X (against a zero-outcome alternative). Lottery risk (variance) increases quadratically with reward and with probabilities approaching 0.50.

Normative Models Assume Rational Movement Decisions

Normative models of motor control typically maximize an average reward or minimize an average cost. As such, these models compute a risk-neutral movement solution, which is akin to rationality. A well-studied task involves subjects making rapid pointing movements to overlapping circular targets that offer rewards and penalties (26,27). Subjects' actual movement end points in this task are similar to those predicted by a model that maximizes average reward, suggesting that subjects selected a risk-neutral motor plan based on the extrinsic costs of the pointing task. However, subsequent work has shown that humans inaccurately estimate their motor variability but in a way that does not detract from near-optimal performance in this particular pointing task (35). Given the dependence of risk attitudes on outcome probability, it is questionable whether the risk neutrality manifested in the pointing task would transfer to other paradigms.

Another type of model often used in motor control is derived from optimal control theory (OCT). OCT provides an elegant mathematical framework to transform symbolic high-level movement tasks into low-level details required by the motor system. Optimal feedback control models integrate sensory and motor noise in their representation of the biomechanical system, and they select the movement that minimizes a cost function. A distinctive feature of these models is that they reduce variability (and, therefore, risk) in task-relevant dimensions, preferentially controlling variability that would interfere with task goals but allowing it to accumulate in task-irrelevant dimensions (24). A relevant future question, then, is whether rationality is more, less, or equally present for task-relevant dimensions compared with task-irrelevant dimensions. And although optimal feedback control has been proven to be a powerful tool in analyzing movement behavior, the form and weighting of the components in these functions remain an open problem in motor control. Accurate construction of the cost function is critical in characterizing and predicting movement behavior, but classical optimal control models would not be able to account for risk-seeking or risk-averse behavior.

Although normative models can be used to quantify risk sensitivity relative to a rational decision maker, they do not provide additional information about where irrationality stems from in the movement planning and execution process. To quantify irrationality further, we can turn to a different class of models that use principles from economic decision making.

Neuroeconomic Models Account for Irrational (Risk-Sensitive) Movement Decisions

Neuroeconomic models of motor control have been developed recently to characterize possible irrationalities in movement. These descriptive frameworks quantify subject-specific sensitivity toward outcome variance, thereby recognizing risk-seeking or risk-averse behavior. Risk sensitivity parameters have been included in models of optimal control (14) and Bayesian integration (8). These models evince that risk sensitivity can explain motor behavior when there is variance in the relevant performance measures. For example, Nagengast *et al.* (14) used a risk-sensitive optimal controller to assess behavior in a continuous

ARM/steering task in the presence of sensorimotor noise. They found that subjects exerted more effort to reduce error, which is consistent with risk-averse behavior and suggests an irrational trade-off between effort and error.

The cumulative prospect theory (CPT) is a particularly useful neuroeconomic model for its ability to parse out relative sensitivities to outcome value and outcome probability. More specifically, CPT quantifies risk-seeking or risk-averse behavior through distortions in the (i) value function and (ii) probability weighting function (28). A value function describes how the subjective valuation of an outcome changes with different outcomes. For instance, people tend to perceive the difference between \$5 and \$10 as more meaningful than the difference between \$105 and \$110, even though the objective difference is \$5 in both cases. This is an example of diminishing sensitivity to increasing outcomes. The value function often is modeled with a power function (28), in which valuation of rewards and penalties is determined by parameters α and β, respectively:

$$v(X) = \begin{cases} X\alpha, & X \geq 0 \\ -(-X)^{\beta}, & X < 0 \end{cases} \tag{2}$$

Probability weighting relates the likeliness of an outcome to the desirability of that outcome. Economic studies have shown that individuals weight probabilities nonlinearly, usually overweighting small probabilities (unlikely events) and underweighting large probabilities (likely events). We use Prelec's probability weighting function (22) to model this S-shaped curve, in which parameter γ dictates the extent of curvature:

$$w(p) = exp\,[-(-\,ln\,((p)^{\gamma]}, 0 < p < 1 \tag{3}$$

Distortions in value and probability weighting (α, β, $\gamma \neq 1$) characterize risk-sensitive behavior, with α, $\beta < 1$ indicative of undervaluing rewards and penalties (risk aversion in gains, risk seeking in losses) and $\gamma < 1$ signifying an underweighting of large probabilities and an overweighting of small probabilities. Conversely, α, $\beta > 1$ indicates overvaluing rewards and penalties (risk seeking in gains, risk averse in losses), and $\gamma > 1$ corresponds to overweighting large probabilities and underweighting small probabilities.

Several studies have used CPT to assess risk sensitivity in discrete movement decisions, when subjects chose between motor "lotteries" for a pointing task (10,33,34). These studies have observed marked distortions in reward valuation and probability weighting, suggesting irrationality/risk sensitivity in these movement tasks. Until recently, it was not known whether such irrationalities were present in movements other than reaching or pointing nor whether irrationality was influenced by emotional processes. To further probe movement rationality, we performed a series of experiments to quantify and compare risk sensitivity across different movements (ARM and whole-body (WB) leaning) using different task paradigms (continuous movement measured against a normative model and discrete movement measured against a CPT model) and different levels of threat (low elevation and high elevation).

IRRATIONAL MOVEMENT BEHAVIOR UNDER IMPLICIT RISK WITH EXPLICIT COSTS

We first sought to compare within-subject risk sensitivity between two fundamentally different types of movements — namely, ARM and WB leaning. Risk sensitivity in ARM or pointing movements has been addressed previously using a number of different paradigms (for a summary, refer to (2)). However, risk is arguably more relevant to whole-body movements, where inappropriate decisions can result in postural instability or even a fall. The goal-directed whole-body movements we examined, in which the center of pressure is moved forward rapidly approximately 5–7 cm in an out-and-back fashion, also are less familiar than equivalent out-and-back ARM, so similar risk sensitivities between ARM and WB tasks would be a strong demonstration of generalization. On the other hand, if behavior under risk did not transfer between the two movements, this would establish dependence of risk sensitivity on movement context. Experimental setups for the two movement tasks are depicted in Figure 3A. Subjects controlled a cursor on the monitor in front of them with a robotic arm in the ARM task or with their center of pressure in the WB task. We used both a continuous movement (moving toward a virtual "cliff") and a discrete movement (hitting a target of varying width) paradigm to measure risk sensitivity and compare between the ARM and WB tasks.

Continuous Movement Paradigm

In our first study (15), we examined a continuous movement decision task under implicit risk and with explicit rewards and penalties. We simulated the paradigm of approaching the edge of a cliff where there is a trade-off between the reward afforded by the view and the penalty incurred by falling over the edge. The optimal end point relative to the cliff edge maximizes the view while minimizing the chance of falling over the edge. The monitor mounted in front of the subject displayed a cursor, a starting position, and a penalty region (cliff) set at two thirds of the subject's maximum movement distance (mean cliff distance: 15.4 ± 3.2 cm for ARM and 5.9 ± 1.4 cm for WB). Subjects were instructed to make swift out-and-back movements, moving the cursor as close to the edge of the cliff as possible without falling over the edge and returning to the starting position. They received a point score for each trial based on the cursor's maximum excursion toward the cliff edge. On the "safe" side of the cliff, points were awarded as a linear function of movement distance, with the maximum possible score of 100 points awarded for moving the cursor perfectly to the edge. A different score was given if the cursor moved into the cliff region. We manipulated risk by increasing the point penalty associated with the cliff region and by adding variability to the cursor feedback. Subjects performed 120 trials in four conditions, including 1) low penalty, low noise (trial score was 0 point if the cursor entered the cliff region, with no added cursor variability); 2) low penalty, high noise (trial score was 0 point if the cursor entered the cliff region, and Gaussian noise was added to the cursor position in the direction of movement); 3) high penalty, low noise (trial score was −500 points if the cursor entered the cliff region, with no added

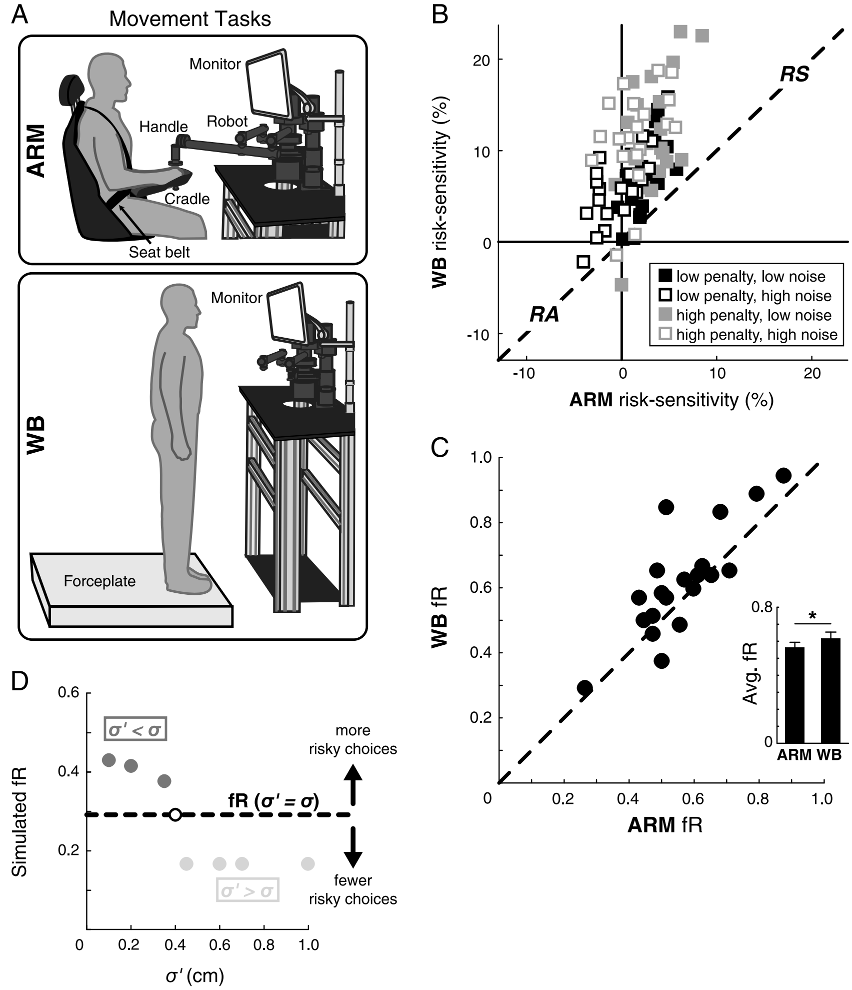

Figure 3. Risk-seeking behavior is stronger in whole-body movements than in arm reaching (ARM). A. Experimental setup for ARM and whole-body (WB) movement tasks. Subjects control a cursor on the monitor using a robotic manipulandum or using their center of pressure. B. Risk-sensitivity metric in continuous movement paradigm, moving a cursor to the edge of a virtual cliff. Data that fall in the upper right quadrant correspond to risk-seeking behavior in both tasks (RS). Data that fall in the lower left quadrant correspond to risk-averse behavior in both tasks (RA). Unity is shown as a *dashed black line*. The degree of risk sensitivity is greater in the WB task (*i.e.,* more risk seeking in WB than ARM). C. Frequency of risky choices (fR) in a discrete movement paradigm, choosing between lotteries with different rewards and target widths. Most subjects chose risky options more often in WB than in ARM, illustrated with most data falling above unity and in average fR (inset; $^*P = 0.018$). D. Misestimating motor variability σ would affect the frequency of risky choices (fR) in a lottery series. Believing yourself to be *more* accurate than you actually are (*dark gray*: $\sigma' < \sigma$) *increases* the number of risky choices, whereas believing yourself to be *less* accurate than you actually are (*light gray*: $\sigma' > \sigma$) *decreases* the number of risky choices. The simulated subject depicted here has actual movement variability $\sigma = 0.40$ cm, but this particular pattern of σ' affecting fR holds across values of σ. [Adapted from (15). Copyright © 2013 The American Physiological Society. Used with permission.] [Adapted from (17). Copyright © 2015 Frontiers. Used with permission.]

cursor variability); and 4) high penalty, high noise (trial score was −500 points if the cursor entered the cliff region, with Gaussian noise on cursor position). We compared subjects' actual end points to those predicted by a risk-neutral movement planning model that maximized point score.

In both movements, most subjects moved closer to the cliff than predicted by the risk-neutral model, indicative of risk-seeking behavior. They were significantly more risk seeking in the WB task across conditions, moving much closer to the cliff edge (and often traversing the edge) than suggested by our risk-neutral model. Figure 3B illustrates risk sensitivity in each task, quantified as a percentage between each subject's actual movement end points and their model-predicted end points. A risk sensitivity of 0% indicates perfect agreement between the model prediction and the subject behavior (risk neutral). A positive risk sensitivity indicates that a subject moved farther than the model predicted (risk seeking), and a negative value indicates that a subject did not move as far as the model predicted (risk averse). Least-squares linear regression of group WB risk sensitivity against ARM confirms that subjects were more risk seeking in WB (slope, 7.2; R^2 = 0.30; F = 22.3; $P < 0.0001$). This finding held at the subject level; across subjects, the slopes of the regression line between conditions were significantly greater than unity ($P < 0.001$), with a mean (±SD) slope of 6.1 (±4.1) and a mean (±SD) R^2 of 0.36 (0.29).

From this study, we concluded that individuals exhibit irrationality in these two dissimilar movements. Subjects were risk seeking in both tasks but significantly more risk seeking in a WB leaning movement than in ARM.

Discrete Movement Paradigm

We also compared ARM and whole-body risk sensitivity with a discrete lottery-based paradigm, specifically probing internalizations of reward and probability (17). Subjects were asked to choose between two lotteries, each of which had a different monetary reward (gains ranging from \$2.40 to \$48) and probability of winning that reward (ranging from 0.05 to 0.95). These probabilities were presented implicitly using targets of varying widths. Target widths were tied to each subject's mediolateral end point variability in that movement task, so a 0.50 probability would be portrayed as a target that the subject would be able to hit in approximately 50% of attempts. To win the monetary reward associated with the target, the subject would have to hit (not miss) the target with an out-and-back movement.

For every choice trial, there was one "safer" lottery and one "riskier" lottery, classified based on the variance of each lottery. We computed the frequency of risky choices (fR) by comparing how many times a subject chose the riskier lottery over the safer lottery to the total number of trials in a task. This fR metric provides a global view of risk-seeking behavior that we can compare across conditions. Figure 3C plots individual and average fR for the ARM and WB tasks. The line of unity represents an identical fR between the two motor tasks at that elevation, whereas the space above unity indicates more risk-seeking behavior in the WB task compared with the ARM task, and the space below unity indicates more risk-seeking behavior in the ARM task compared with the WB task. Most subjects have a WB fR that is nearly equal to or greater than their ARM fR, illustrating between-subject consistency in having more risky choices in the WB task than in the ARM task. Indeed, average fR is greater in the WB task than in the ARM task ($P = 0.018$), with mean (± SEM) values of 0.56 (0.03) for ARM and 0.62 (0.04) for WB.

In this discrete paradigm, as in the continuous paradigm, subjects were risk seeking in both motor tasks but significantly more risk seeking in a WB leaning movement than in ARM.

WHY IS THERE A DIFFERENCE BETWEEN MOVEMENT TASKS?

Sitting and Standing Postures Do Not Affect Risk Sensitivity

Was this difference in risk sensitivity caused by the types of movement or simply because of the sitting and standing postures? Certain body postures have been shown to evoke various physical and neurobiological changes. More comfortable postures have been shown to enhance performance in memory tasks (11,35), whereas less comfortable positions can improve reaction time (32). High-power poses, in which the body is open and expansive, can lead to increased feelings of power and more risk-seeking behavior in a loss-based gambling task (5). Thus, it is possible that the difference in risk sensitivity between the ARM and WB tasks could be attributed to their respective sitting and standing postures. We sought to differentiate possible changes in risk sensitivity caused by the postures themselves with a nonmotor task (16). Using a similar lottery paradigm as described in the previous section, subjects made a series of choices between two economic lotteries with different monetary rewards and explicitly stated probabilities of winning that reward. They made these economic choices while sitting and while standing, and we compared risk sensitivity between the two postures through the same fR metric as well as through the subjective valuation and probability weighting parameters fit using CPT.

Subjects made similar economic lottery choices irrespective of body posture. Mean (± SEM) fR values were 0.51 (0.05) for sitting and 0.49 (0.05) for standing, and paired *t*-tests yielded no significant differences in fR between the two postures. Median and 95% confidence intervals for the CPT parameter fits suggested diminishing sensitivity to value ($\alpha_{sit} = 0.52$ (0.20, 1.38); $\alpha_{stand} = 0.68$ (0.28, 1.23)) and a slight tendency to underweight large probabilities ($\gamma_{sit} = 0.91$ (0.39, 1.22); $\gamma_{stand} = 0.90$ (0.52, 1.24)). However, again, there was no significant difference between movement tasks for either parameter. Because sitting and standing postures did not affect choices in this economic decision-making task, the aforementioned differences in risk sensitivity between the ARM and WB movements must result from other characteristics of the movements besides their required postures.

Valuation of Explicit Costs

We ran an additional CPT analysis on both the continuous movement (cliff) and discrete movement (lottery) study. In the continuous movement, most subjects (17 of 20) overvalued the point rewards ($\alpha > 1.0$), undervalued penalties ($\beta < 1.0$), or overweighted the probability of a movement end point ($\gamma > 1.0$) in both ARM and WB tasks. Such directionality is consistent with risk-seeking behavior. For the two value parameters, α and β, there were significant differences between the ARM and WB tasks (α: $P = 0.0002$; β: $P = 0.0001$), indicating that distorted valuation of rewards and penalties is larger in the WB movement. There is no significant difference in the variability parameter γ between ARM and WB ($P = 0.087$).

Greater overvaluing of reward and undervaluing of penalty in the WB movement could explain more risk-seeking behavior observed in this task, prompting subjects to move closer to the cliff edge to obtain a higher reward with less fear of receiving the cliff penalty. However, we do not think that this is the primary cause of greater risk-seeking behavior in WB for several reasons. First, the point structure was the same in both the ARM and whole-body tasks, and there is no obvious reason why the same subject would value the points differently between tasks. Even if a distorted value function does exist, this distortion should remain consistent between tasks, which is not what we observed. Second, leaning forward moves the center of pressure closer to the limits of stability while standing, inherently increasing the chance of a fall and thereby adding an implicit penalty over and above the explicit point penalties presented to the subject (1). This should induce an overweighting of the point penalties and result in a more risk-averse behavior compared with the ARM task. We propose that still other factors contribute to the increased risk-seeking behavior observed in WB movements.

Valuation of Implicit Costs

In the context of OCT, the different risk sensitivities in ARM and WB tasks could be a manifestation of different cost functions between the two movements. Typical cost functions in optimal motor control models include terms to penalize error and effort. By adding a risk sensitivity term, as in (14), the implicit error and effort costs can be compared across movements in addition to the degree of risk sensitivity. Different movements may indeed have dissimilar weightings on other costs. If they also have dissimilar weightings on risk sensitivity term, this would validate the dependence of risk sensitivity on movement task.

Underestimating Motor Variability Increases Risky Choices

Another possible explanation for the observed differences between the ARM and WB tasks is differing estimations of end point variability, σ. It has been shown previously that humans have notably inaccurate models of their own end point distributions during a pointing task, with some drastically underestimating their variability (35). We next simulated how various estimations of motor variability would affect the frequency of risky choices in the discrete lottery paradigm. Overestimating or underestimating variability would alter perception of the lottery probabilities, σ'. For each trial, a simulated subject chooses the lottery with a higher expected value, computed using the perceived probabilities. If the selected lottery also is riskier according to the original (undistorted) probabilities, then the number of risky choices increments. Figure 3D compares fR for numerous values of σ'. Underestimating motor variability ($\sigma' < \sigma$; thinking you are more accurate than you actually are) results in a higher fR, whereas overestimating motor variability ($\sigma' < \sigma$; thinking you are less accurate than you actually are) results in a lower fR. This analysis verifies that distorted perceptions of end point variability influence choice behavior and may in part explain why subjects choose riskier lotteries in the WB task. Thus, risk-seeking behavior in the WB movement may result from a greater underestimation of motor variability. To further elucidate the impact of variability estimation on risk attitudes, future work should compare experimentally humans' perceptions of variability in different movements, such as the ARM and WB tasks described here.

We believe underestimation of variability to be a plausible explanation, particularly given the unfamiliarity of the WB motor task. Although forward-leaning movements are relatively common in everyday tasks (such as when reaching for a cup in a high cabinet), such movements tend to involve slow small leaning distances. The rapid, out-and-back, goal-directed center of pressure movements used in our experiments is more challenging and is not often experienced on a daily basis. This could account for an inability to internalize appropriately one's sensorimotor variability within the duration of this experiment.

We summarize this main finding in Figure 1A, wherein subjective distortions in motor variability (specifically, underestimating variability) increase risky decisions.

THREAT EXACERBATES IRRATIONALITY IN RELEVANT TASKS

Recent work suggests that an individual's emotional state can dictate decision making. For instance, affective reactions to a stimulus, either positive or negative, can alter our subjective interpretations of perceived risks and benefits, thereby impacting our cognitive processes and choices (25). Stress — such as one might experience before delivering a public speech or while immersing one's hand in icy water — specifically has been shown to modulate risk sensitivity in economic decision making. Stressed participants reduce their risk-taking behavior in the face of potential monetary losses (19), increase risk taking for potential monetary gains (4), or *vice versa* (20). We examined the influence of postural threat on risk sensitivity during nonmotor and motor decision making. Subjects again chose between risky lotteries in the economic (sitting and standing; monetary rewards with explicit probabilities) and motor (ARM and WB; monetary rewards with target widths based on probabilities) domains. They completed each task at ground level (low condition) and atop a 0.8-m elevated platform (high condition).

Postural Threat Increases Physiological Arousal and Decreases End Point Variability

Increasing elevation resulted in two important behavioral changes. First, skin conductance level (SCL) to determine whether the increased elevation altered physiological arousal. For each economic and motor task, average SCL was significantly higher for the low condition than during a baseline measurement of quiet sitting for 5 min ($P < 0.001$). Similarly, across tasks, average SCL at high elevation was significantly higher than at low elevation ($P < 0.002$), indicating that subjects responded physiologically to this form of postural threat. Paired *t*-tests reveal a significant difference in variability between elevation conditions, where σ_{High} is smaller than σ_{Low} for both the ARM task ($P = 0.032$) and the WB task ($P = 0.034$). Elevation did not significantly affect fR in any task.

TABLE. Median cumulative prospect theory parameter fits (lottery paradigm).

Task		α	γ
Nonmotor (economic) lotteries	SIT Low	0.52 (0.20, 1.38)	0.91 (0.39, 1.22)
	STAND Low	0.68 (0.28, 1.23)	0.90 (0.52, 1.24)
	SIT High	0.67 (0.20, 1.51)	0.79 (0.62, 1.07)
	STAND High	0.37 (0.25, 1.40)	0.72 (0.45, 1.34)
Motor lotteries	ARM Low	0.68 (0.34, 0.88)	0.97 (0.81, 1.06)
	WB Low	0.72 (0.29, 0.96)	0.99 (0.75, 1.06)
	ARM High	0.53 (0.29, 0.87)	0.90 (0.67, 1.15)
	WB High	0.49 (0.36, 0.92)	0.82* (0.46, 1.06)

Median α and γ values with 95% confidence intervals. Asterisk (*) indicates a significant difference from low elevation within motor task ($P < 0.05$). [Adapted from (15). Copyright © 2013 The American Physiological Society. Used with permission.] [Adapted from (16). Copyright © 2014 PeerJ, Inc. Used with permission.]

ARM, arm reaching; WB, whole body.

Interestingly, there is a moderate negative correlation between these two factors in the WB task ($\rho_{WB} = -0.54$; $P = 0.01$). That is, subjects who exhibited greater increases in arousal at high elevation also exhibited greater decreases in variability at high elevation, suggesting that they tightened control of their center of pressure.

Postural Threat Does Not Affect Choices in the Economic or ARM Domains

Median CPT parameter fits and 95% confidence intervals are given in the Table. For both economic tasks (sitting and standing) and for the ARM task, these median fits suggest diminishing sensitivity to monetary rewards ($\alpha < 1$; SIT Low: 0.52, SIT High: 0.67, STAND Low: 0.68, STAND High: 0.37, ARM Low: 0.97, ARM High: 0.90) and a slight overweighting of small probabilities ($\gamma < 1$; SIT Low: 0.91, SIT High: 0.79, STAND Low: 0.90, STAND High: 0.72, ARM Low: 0.97, ARM High: 0.90). Such trends hold for both elevations, and there were no significant differences in α or γ parameters between elevation conditions for any of these tasks. Median value and probability weighting curves for the ARM task are given in Figure 4A.

Postural Threat Induces More Cautious Choices for Whole-Body Movements

At both elevations, median fits for the WB task also correspond to diminishing sensitivity to value ($\alpha < 1$; WB Low: 0.72, WB High: 0.49) and overweighting small probabilities ($\gamma < 1$; WB Low: 0.99, WB High: 0.82), as shown in Figure 4B. Importantly, the γ values in WB High are significantly smaller than those in WB Low ($P = 0.049$). In accordance with the fourfold pattern of risk attitudes implicated in CPT (28), greater overweighting of small probabilities corresponds with more risk-seeking behavior for small probability gains and more risk-averse behavior for small probability losses. In the context of movement control, successful target acquisition can be considered a gain, whereas movement errors are synonymous with losses. Thus, a concave utility function and the direction of the median probability weighting functions suggest increased risk aversion toward movement errors at high elevation. Note that our CPT analysis in this discrete lottery paradigm did not uncover differences in reward-based value functions between ARM and WB (black curves in Fig. 4), confirming that valuation of explicit rewards is similar between the two motor tasks.

We summarize this main finding in Figure 1B, wherein subjective distortions in probability weighting (specifically, overweighting small probabilities and underweighting large probabilities) decrease risky decisions for salient movements.

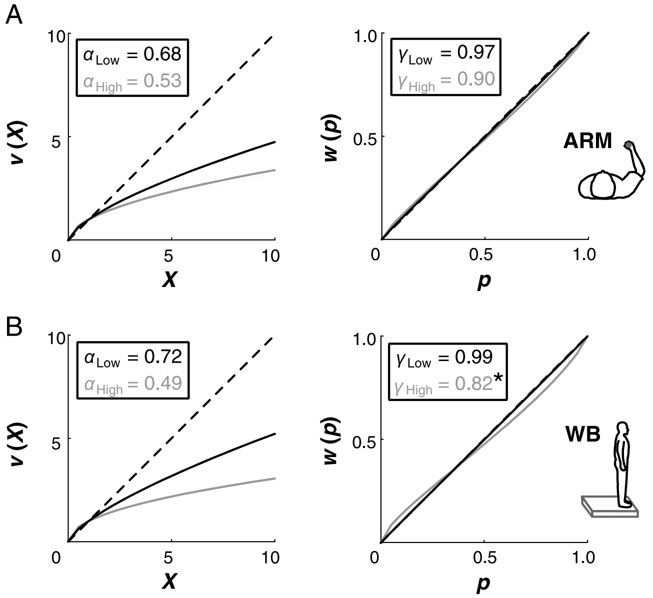

Figure 4. Effect of postural threat on arm-reaching ARM and whole-body (WB) risk sensitivity. Cumulative prospect theory model fits for the subjective value ($v(X)$) and probability weighting functions ($w(p)$) in the (A) ARM and (B) WB lottery tasks. Curves correspond to median fits for low elevation *(black)* and high elevation *(gray)*. Probability weighting parameter γ is significantly lower in WB High than in WB Low (*$P = 0.049$), suggesting that there is a greater distortion in probability representation under increased threat for the WB task. Subjects underweighted large probabilities more in WB High, suggesting a more cautious movement strategy. [Adapted from (17). Copyright © 2015 Frontiers. Used with permission.].

CONCLUSIONS

By relating neuroeconomic principles to ARM and whole-body movements, we have found that individuals exhibit distinct irrationalities in movement, meaning they do not objectively account for the uncertainty, costs, and rewards associated with these movements. In particular, we observed risk-seeking behavior in goal-directed ARM and WB leaning movements, as well as distorted probability weighting under threat. We posit that human movement decisions are peppered with such irrationalities, which are influenced by inaccurate estimations of motor variability and emotional state in relevant movement tasks.

Acknowledgments

This study was supported by the Defense Advanced Research Projects Agency Young Faculty Award (DARPA YFA D12AP00253) and by the National Science Foundation (SES 1230933 and CMMI 1200830).

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