Psychology of Sport & Exercise 73 (2024) 102618

Contents lists available at ScienceDirect

Psychology of Sport & Exercise

journal homepage: www.elsevier.com/locate/psychsport

The impact of task (un)certainty on repeated grip force production

Aviv Emanuel [a,b,c,*], Idan Haklay [a], Itai Har-Nir [b,c], Israel Halperin [b,c], Nira Liberman [a,d]

[a] School of Psychological Sciences, Tel-Aviv University, Tel-Aviv, Israel
[b] Department of Health Promotion, School of Public Health, Faculty of Medical & Health Sciences, Tel-Aviv University, Tel-Aviv, Israel
[c] Sylvan Adams Sports Institute, Tel Aviv University, Tel-Aviv, Israel
[d] International Faculty, Key Profile Area II: Behavioral Economic Engineering and Social Cognition, University of Cologne, Germany

ARTICLE INFO

Keywords:
Effort
Fatigue
Pacing
Uncertainty
Motivation

ABSTRACT

Many studies found that in physical tasks, reducing certainty regarding their endpoints hinders performance. However, the impact of reducing certainty regarding other aspects of physical tasks is unknown. Here we manipulated the certainty of the required effort on an unrelated, parallel task (i.e., *off-task uncertainty*) and examined how it impacts force production in two within-subject experiments (N = 79). In two sessions, subjects completed 20 repetitions composed of maximal forces using a gripper with their dominant hand. Between repetitions, participants applied either submaximal constant or varied grip forces, with their non-dominant arm, matched for total forces across repetitions. While we observed trivial differences in total forces between conditions, under the varied condition, participants produced a steeper decrease in forces, suggesting that off-task uncertainty impacted their effort allocation strategy. We speculate that this pattern can be attributed to cognitive overload and/or changes in motivation stemming from the imposed uncertainty.

People routinely exert effort to achieve their goals, but deciding how to distribute effort in the course of goal pursuit is no trivial task.[1] For example, a person who must quickly reach an airport gate can walk, jog, or sprint. If the gate is not too far and the person is physically fit, then sprinting there as fast as possible–the so-called “all out” strategy–would be a good idea. Conversely, if the gate is further away and the person is physically inactive, then implementing a more moderate strategy, such as walking at an above-average, constant pace would probably get them to the gate faster.

Importantly, however, for all people—sedentary and elite athletes alike–tasks of longer durations or distances would require moderating effort (i.e., pacing) (E. J. Allen et al., 2016; McGibbon et al., 2018). For example, in running races over 800 m, even elite runners do not implement an “all out” strategy, but instead follow moderate energy expenditure strategies (Tucker et al., 2006). Although the literature suggests that people regulate effort in view of prospective task demands (Braver, 2012; Noakes, 2007), little is known about what instigates this process and what moderates it.

One variable that has been shown to affect pacing is certainty regarding task endpoint, which implies certainty about the extent of effort the task would require over time. When people do not know the distance, time, or number of repetitions that they would need to complete, they tend to underperform compared to conditions with a clear endpoint. For example, people run and cycle slower, and apply lower forces in resistance tasks when uninformed about the task endpoint (Cheema & Bagchi, 2011; Halperin et al., 2014; Hanson & Buckworth, 2015; Wingfield et al., 2018). It can be speculated that when people are unsure as to the extent of effort that will be required over time, they resort to a frugal policy, and apply a lower level of effort to conserve energy in view of possible high future demands.

Importantly, uncertainty in these studies concerned the overall demands on the performing muscle-groups, that is, the same muscle-groups *whose output was measured (i.e., task-specific uncertainty)*. For example, people’s force output was measured with and without knowledge as to how many repetitions they would need to complete (Halperin et al., 2014). In conditions of task-specific uncertainty, applying moderate levels of effort makes sense. This is because people prepare for the possibility of longer effort expenditure and assume that

* Corresponding author. School of Psychological Sciences, School of Public Health and Sylvan Adams Sports Institute, Tel Aviv University, Tel Aviv, Israel.
E-mail addresses: avivemanuel@mail.tau.ac.il, aviv.emanuel@gmail.com (A. Emanuel).

[1] We use the term *“effort”* to refer to the mobilization of resources to carry out instrumental behavior (Gendolla & Wright, 2009). Effort is a latent variable estimated by objective and observable performance or physiological variables. For example, force production, lifted loads, heart rate, and oxygen consumption. In this study, we use force production as the observable output that is indicative of effort. Note that effort is associated with such observable variables but is not identical to them. For example, when sick, a person might need to exert more effort to produce the same level of force as when healthy.

https://doi.org/10.1016/j.psychsport.2024.102618
Received 17 April 2023; Received in revised form 8 November 2023; Accepted 5 March 2024
Available online 13 March 2024
1469-0292/

for a specific muscle group, moderate effort can be exerted over longer durations/distances than more intense effort.

A question that remains unanswered is how other types of uncertainty would affect effort allocation. More specifically, would increasing uncertainty regarding the demands on one muscle group cause a frugal, more moderate pattern of effort allocation in another muscle group? This could be expected if frugality does not reflect prospection about the performance of specific muscles, but rather a general response to many types of uncertainty, a policy that says "in an uncertain situation, spend energy resources frugally". Conversely, it is also possible that uncertainty, when it does not concern the performing muscles, would interfere with planning, causing one to invest effort in a myopic, present-oriented (rather than frugal, future-oriented) manner.

In two studies we set out to examine how force allocation would be affected by uncertainty regarding force requirements that do not concern the performing muscles. For that end, we manipulated uncertainty regarding moment-to-moment force requirements in a concurrent task that involved different muscle groups than the main task. We term this *off-task* uncertainty. To examine the effect of off-task uncertainty on effort allocation we developed a paradigm in which the dependent variable was force applied over 20 repetitions by one arm (when the instructions are to produce maximum force), and the independent variable is the force applied after each such repetition by the other arm, which, depending on the experimental condition, was either constant and certain, or varied and uncertain, but similar on average between the two conditions.

The difference between this type of uncertainty and uncertainty regarding the task's end point (i.e., *between off-task uncertainty* and *task-specific uncertainty*) should be emphasized: In task-specific uncertainty, the actors do not know the extent of effort that would be required of the muscle groups that are directly involved in completing the task, so a reasonable strategy is frugality, that is, start moderately, preparing for the possibility of a longer task. In off-task uncertainty, on the other hand, uncertainty concerns only moment-to-moment demands of the muscle groups that are not performing the main task.

Would off-task uncertainty induce a frugal, conservative effort allocation strategy? In other words, would off-task uncertainty, just like task-specific uncertainty, induce a lower-level of force across the repetitions, and a more moderate decline in force over repetitions in comparison to a condition with no uncertainty? Or would off-task uncertainty, conversely, interfere with planning and drive people to a myopic, rather than a frugal allocation of effort over the course of a task? This would be manifested in starting with a higher level of force and a reducing force more steeply over repetitions, akin to an "all-out" strategy.[2] We further elaborate on the importance of this question in the general discussion, where we address it in light of the results.

1. Experiment 1

We tested whether introducing off-task uncertainty about the upcoming required level of force would reduce level of applied force, or rather cause a more myopic pattern of force allocation, namely, a steeper reduction in applied force. We asked participants to perform 20 Maximum Voluntary Contractions (MVCs) with their dominant hand. Before each repetition, they were instructed to exert with their non-dominant hand a force that was either fixed (fixed condition) or had the same mean value but varied randomly through the session (varied condition). We examined whether the level of exerted peak force (measured as % of pretest MVC) would be lower in the varied than in the fixed condition, whether it would be reduced over the 20 repetitions, and whether the reduction would be steeper in the varied condition than in the fixed condition.

1.1. Method

1.1.1. Participants

Forty-three participants (21 women; $M_{\text{age}} = 29.60$, $SD = 8.79$) were recruited in exchange for course-credit. We aimed to continue data collection until we reached 40 participants with full data. One participant was excluded for not feeling well during the second session, and two additional participants were excluded because, due to an experimenter's mistake, they performed the same experimental condition twice.

1.1.2. Materials and procedure

All materials and procedures for this and the subsequent study were approved by the Tel-Aviv University institutional review board. Participants were asked to watch a short video that demonstrated the experimental procedure before they arrive at the lab. They also provided information on their age, gender, and dominant hand. Participants performed two experimental sessions with an interval of at least 48 h between them. Before each experimental procedure in each session, participants performed four pre-test measurements of their grip-force MVC in each hand which lasted 3 s and were interspaced with 40 s of rest. In the first two pre-test repetitions in each hand, participants could not see the force they were producing, but in the last two repetitions they could.

In each session, after a pre-test MVC measurements (see below) and a 3-min break, participants performed 20 repetitions of producing MVC with their dominant hand. Each repetition lasted 3 s. Before each repetition with their dominant hand, participants were asked to use their non-dominant hand to produce for 3 s a force equal to a number presented on the computer screen. There were 10 s between every two repetitions. In the fixed condition, the number on the computer screen was identical for every repetition, and was equal to 60% of the peak they achieved with the non-dominant had during the pre-test measurements on that day. In the varied condition, the number on the computer screen varied from trial to trial and was drawn at random from a normal distribution with a mean of 60%, and a standard deviation of 17% of the peak force of the non-dominant hand they achieved during the pre-test measurements on that day. Participants had 10 s to switch between generating the instructed force with their non-dominant hand and generating MVC with their dominant hand. At the top of the computer screen, a progress-bar and a counter were displayed, which indicated the number of repetitions left until the end of the session (Figure 1). The experimenter noted out-loud when participants had 20 more repetitions left overall (10 in each hand), and when they reached their last repetition for the session. Grip-force was measured with a grip dynamometer (Kinvent, Orsay, France) with a sampling frequency of 75 Hz and a designated tablet app (K-APP, Orsay, France). The instructions and progress bar on the computer screen were presented via the Matlab software (Version R2017; www.mathworks.com) and the Psychtoolbox package (Version 3).

Each session began with a warmup and familiarization procedure, whereby we introduced (in the first session) or reminded (in the second session) participants of the squeezing technique and explained to them that the tablet app displays the force they generate. We instructed participants to sit with their back straight, their feet on the floor, their non-squeezing arm on their shoulder, and their squeezing arm straight to the side of their body, not touching the seat. After a short demonstration of a 15-s squeeze, we asked participants to familiarize themselves with the equipment by freely using the handgrip dynamometer and observing the values displayed on the screen for 15 s for each hand. Afterwards, we introduced the instructions on the computer screen as shown in Figure 1, and asked participants to perform four repetitions with each hand with the force 4, 6, 15, 7, and 15, 7, 6, 4 kg in the right and left hand, respectively for women, and 8, 12, 10, 20, and 20, 8, 12, 10, for the left

[2] Of note, we are not suggesting that an "all-out" strategy is necessarily myopic, only that a myopic, present (rather than future-) oriented pattern of effort allocation could give rise to such a strategy.

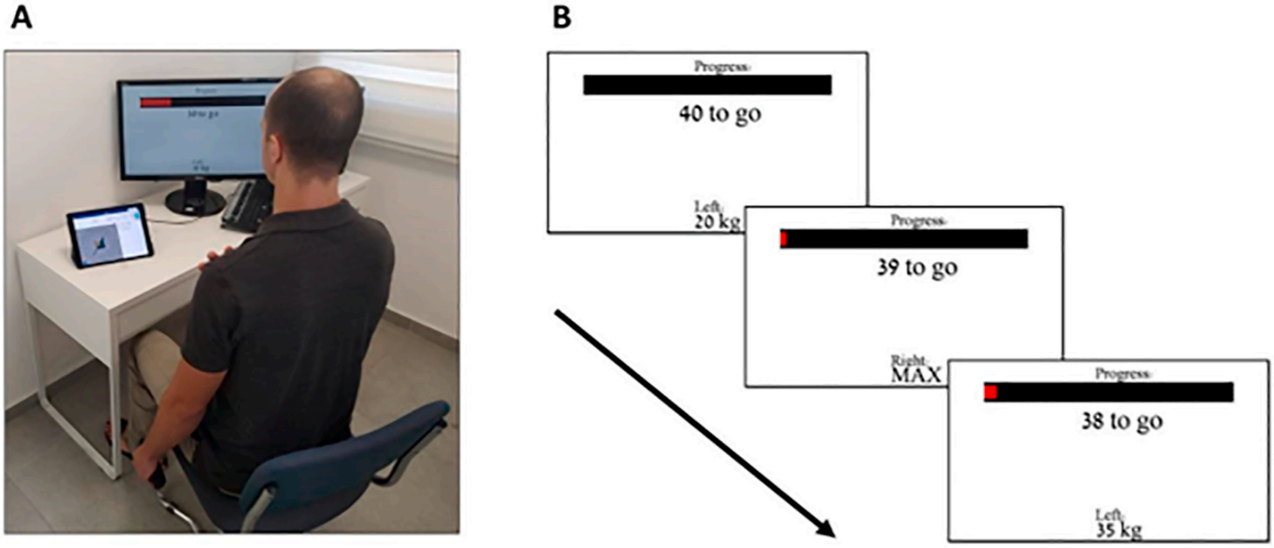

Figure 1. An example of the experimental setup and flow. ***A***. The experimental setup. The participant read the instructions for each repetition from the computer screen, and received feedback regarding their produced grip force via a designated tablet app. ***B.*** An example from the experimental procedure in the varied condition. In the familiarization and experimental procedure, a progress bar at the top of the screen indicated the repetitions performed (red bar) out of the total number of repetitions (black line). Underneath it, a number indicated how many repetitions were left until the end of the block. "Right" or "Left" at the bottom of the screen indicated to participants which hand to use, and the number indicated the target level of force to be produced. There were 10 s between every two repetitions. The first squeeze was always done with the non-dominant hand.

and right hand, respectively for men. We estimated these values to be between 20 and 50% of participants' MVC (Leyk et al., 2007). The first squeeze was always done with the non-dominant hand. As in the experimental procedure, participants performed each squeeze with their non-dominant hand and their dominant hand right afterwards, with 10 s between each two repetitions. The experimenter answered questions and resolved any misunderstandings during the familiarization procedure, and noted when participants had four repetitions left, and then again when they had one repetition left before the end of the warmup. Participants then proceeded to perform the pre-test measurements and the experimental procedure. Before they performed the experimental procedure, the experimenter told participants that the force they will produce with their non-dominant hand will be either fixed (in the fixed condition) or would vary between repetitions (in the varied condition).

The %MVC in each repetition with the dominant hand served as the dependent variable. We calculated this variable by first calculating the pre-test MVC, which was the average peak force of the highest three pre-test measurements on the day of the experimental session. For each participant, the peak force in each repetition was converted into percentages of this value. Statistical analyses and figure making were carried out with R (version 4.0.2; R Core Team, Vienna, Austria) using the ggplot2, cowplot, lme4, lmeTest, dplyr, and tidyr packages.

1.1.3. Results

The data of both experiments are available at https://tinyurl.com/3p6p7adk. We compared the steepness of reduction in %MVC in the varied condition and the fixed condition. Average reduction of effort is best assessed as the steepness of the linear (downward) trend, and thus our main analysis, which we also preregistered in Experiment 2, is a linear regression of %MVC on repetition number. Because the rate of decline in %MVC over repetitions was not constant but rather decelerated (that is, reduction in %MVC from one repetition to the next was more substantial in the beginning of the session than toward its end), a quadratic model fit the data better than the linear trend (*conditional* $R^2_{linear} = 0.76$, *conditional* $R^2_{quadratic} = 0.78$, $p < 0.001$), and we thus report also a quadratic trend analysis, as well as its interaction with condition.

We tested a linear mixed regression model with the %MVC as the dependent variable, and centered repetitions, condition, and their interaction as the predictors, nested within participants. We added a random intercept and additional random slopes for condition and repetitions, as recommended by Bliese and Ployhart (2002). We found that %MVC decreased more steeply over repetitions in the varied condition compared to the fixed condition, $b = -0.116$, $SE = 0.028$, $t(1475.23) = -4.07$, $p < 0.001$, 95% CI [-0.172, −0.060]; see Figure 2.

Importantly, the mean %MVC, across all 20 repetitions, was similar across conditions ($M_{fixed} = 88.41$, $SD_{fixed} = 11.03$; $M_{varied} = 88.47$, $SD_{varied} = 11.30$), $t(39) = -0.03$, $p = 0.976$. A Bayes factor of $BF_{01} = 5.85$, suggested that the hypothesis of no difference in overall %MVC between conditions is more likely than the hypothesis of the existence of such difference.

The quadratic model specifications were identical to the linear model except for an additional repetitions^2 coefficient and its interaction with condition. This model showed a significant effect of repetitions^2, $b = 0.013$, $SE = 0.001$, $t(1470) = 7.40$, $p < 0.001$, 95% CI [0.010, 0.017] that did not interact with condition, $b = 0.004$, $SE = 0.002$, $t(1470) = 1.83$, $p = 0.068$, 95% CI [-0.0003, 0.010]. As in the linear model, the effect of repetition and its interaction with condition were significant (see Table 1).

These results suggest that although the quadratic function describes the overall pattern of results better than a linear function (because rate of decline in effort decelerated over trials), the difference between condition is best described as a difference in (mean) rate of decline in effort over repetitions. This decline was steeper in the varied condition than in the fixed condition. Importantly, this was the case even though overall level of effort did not differ between conditions. In other words, participants in the varied condition demonstrated a more pronounced myopic, "all out" strategy of effort allocation, rather than a more frugal, effort conserving strategy.

2. Experiment 2

This experiment was a preregistered replication of Experiment 1. The preregistration is available at https://aspredicted.org/~XRoZIuQd7A.

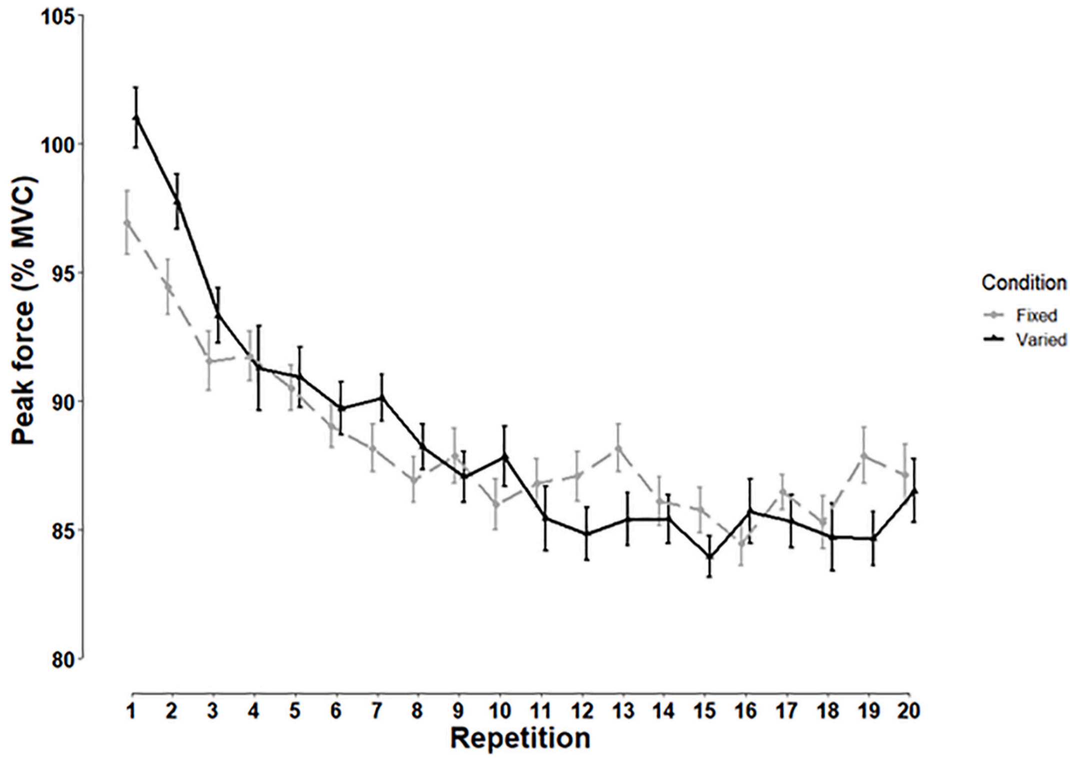

Figure 2. Force production over time in Experiment 1 in the fixed and varied conditions. The Y-axis represents peak force values of each repetition as the percent of the mean peak force from the pre-test measurement on that day for each participant (%MVC). Before each repetition participants produced with their non-dominant hand a target force of 60% of their MVC (in the fixed condition) or a force which was randomly drawn from a normal distribution with a mean of 60% of their MVC and an SD of 17 (in the varied condition).

2.1. Method

2.1.1. Participants

Thirty-six participants (27 women; $M_{age} = 22.90$, $SD = 1.81$) were recruited in exchange for course-credit. Based on the results of the Experiment 1, we extracted a power curve for the coefficient of the difference between the two conditions in the linear trend using the simR package. The curve indicated that ~80% statistical power for the difference in the linear trend between the two conditions can be achieved past a sample of 20 participants. We therefore aimed to continue data collection until we reached a maximum of 40 participants or until the end of the spring semester of 2021. One participant was excluded for not showing up for the second session.

2.1.2. Materials and procedure

All materials and procedures in this experiment were identical to Experiment 1, except that we added, at the end of each of the two sessions, a few control and manipulation-check measures. Specifically, participants reported to what extent the gripper task today was difficult, stressful, interesting, challenging, enjoyable, to what extent they wanted to perform it well, and to what extent they knew what to expect on the next repetition of the handgrip task, all on scales that ranged between "0" ("not at all") to "100" ("very much"). After completing both sessions, participants answered the question "In at least one of the experimental sessions, did you plan ahead whether to apply more or less force while performing the 20 repetitions? (*Yes/no*)".

2.1.3. Results

Manipulation check. Participants indicated that they knew what was expected in the next repetition more in the fixed condition compared to the varied condition ($p = 0.001$, $d = 0.59$; see Supplementary Table 1).

Main Analysis. Similar to Experiment 1, we report both a linear mixed regression model, which more directly tests our prediction, and a quadratic mixed regression model, which provided a better fit to the data (*conditional* $R^2_{linear} = 0.80$, *conditional* $R^2_{quadratic} = 0.81$, $p < 0.001$). Replicating Experiment 1, force decreased more steeply over repetitions in the varied condition compared to the fixed condition, $b = -0.107$, $SE = 0.033$, $t(1293.19) = -3.22$, $p = 0.001$, 95% CI [-0.177, −0.044]; see Figure 3. Also replicating Experiment 1, there was evidence for no difference in %MVC between conditions across all repetitions ($M_{fixed} = 92.96$, $SD_{fixed} = 13.91$; $M_{varied} = 92.86$, $SD_{varied} = 15.10$), $t(33) = -0.03$, $p = 0.970$, $BF = 5.43$. Thus, as in Experiment 1, uncertainty regarding force production in participants' non-dominant hand gave rise to a more myopic distribution of force over time, with steeper decline but similar overall effort.

The quadratic model showed a significant effect of repetition^2, $b = 0.008$, $SE = 0.002$, $t(1270) = -1.90$, $p < 0.001$, 95% CI [0.004, 0.013], which did not interact with condition, $b = 0.001$, $SE = 0.003$, $t(1270) = -0.49$, $p = 0.715$, 95% CI [-0.005, 0.007]. As in the linear model, the effect of repetition and its interaction with condition were significant (see Table 1).

In sum, we found no evidence for a more frugal effort expenditure in the varied condition than in the fixed condition, as participants in both conditions applied the same mean level of force. In both experiments, we found that force decreased over repetitions more steeply in the varied condition than in the fixed condition. The rate with which force decreased over repetitions decelerated over trials (i.e., decrease was steeper in initial than in later trials), but we did not find that deceleration differed between conditions. This pattern of results indicates that whereas a quadratic function describes the overall pattern of results better than a linear function, the difference between condition is best described as "differences in slopes" (i.e., as difference is overall rate of decrease, rather than as a difference in the rate to which this decrease decelerates over time).

Most participants, namely, 83%, reported that they did not plan ahead when to apply more versus less force in any of the experimental

Table 1
Mixed models' results of Experiments 1 and 2.

Variable	Estimate (*b*)	SE	*t*-value (df)	*p*-value	95% CI
Linear model–Experiment 1					
Intercept	92.89	1.81	51.25 (41.22)	<0.001	89.23, 96.55
Repetition	−0.213	0.041	−5.10 (49.70)	<0.001	−0.297, −0.129
Condition: Varied vs. Fixed	2.494	2.17	1.15 (45.64)	0.258	−1.89, 6.88
Repetition X Condition	−0.116	0.028	−4.07 (1475.23)	<0.001	−0.172, −0.060
Quadratic model–Experiment 1					
Intercept	86.58	1.76	49.11 (40.58)	<0.001	83.02, 90.14
Repetition	−0.214	0.041	−5.16 (48.80)	<0.001	−0.297, −0.130
Condition: Varied vs. Fixed	−0.585	2.130	−0.28 (41.20)	0.785	−4.87, 3.70
Repetition^2	0.013	0.001	7.40 (1470)	<0.001	0.010, 0.017
Repetition X Condition	−0.117	0.027	−4.30 (1470)	<0.001	−0.169, −0.063
Repetition^2 X Condition	0.004	0.002	1.83 (1470)	0.068	−0.0003, 0.010
Linear model–Experiment 2					
Intercept	96.44	2.18	44.05 (35.80)	<0.001	91.99, 100.88
Repetition	−0.175	0.036	−4.81 (54.17)	<0.001	−0.247, −0.102
Condition: Varied vs. Fixed	2.29	2.57	0.893 (39.41)	0.377	−2.90, 7.49
Repetition X Condition	−0.110	0.033	−3.28 (1286.50)	0.001	−0.177, −0.044
Quadratic model–Experiment 2					
Intercept	91.59	2.34	39.04 (35.15)	<0.001	86.82, 96.35
Repetition	−0.175	0.036	−4.83 (53.6)	<0.001	−0.247, −0.102
Condition: Varied vs. Fixed	−0.186	2.51	0.17 (35.7)	0.941	−5.27, 4.90
Repetition^2	0.008	0.002	−1.9 (1270)	<0.001	0.004, 0.013
Repetition X Condition	−0.112	0.033	−3.34 (1280)	<0.001	−0.177, −0.044
Repetition^2 X Condition	0.001	0.003	−0.49 (1270)	0.715	−0.005, 0.007

SE = standard deviation, df = degrees of freedom, CI = confidence interval.

sessions. Additional paired t-tests comparing conditions on each of the self-report measures are presented in Supplementary Table 1. There were no differences between conditions in any of the other control variables.

3. Discussion

In two experiments, participants performed 20 gripper MVCs with their dominant hand under two counterbalanced conditions. In the fixed condition, participants applied a force equal to 60% of their pretest MVC with their non-dominant hand before each MVC with their dominant hand. In the varied condition, participants applied a force that varied randomly with a mean of 60% (and a SD of 17) of their pretest peak MVC with their non-dominant hand before each MVC with their dominant hand. We call the uncertainty that is introduced in this condition "off-task uncertainty". In both experiments, participants' grip force declined more steeply across repetitions in the varied condition than in the fixed condition, although the overall force (that is, force observed over the total 20 repetitions) did not differ between conditions. These results suggest that off-task uncertainty does not lead to investing less overall effort across repetitions, but does lead to a different pattern of effort allocation, namely, to an initially higher level of effort that declines faster over time.

In both conditions in both experiments, the produced force gradually decreased with consecutive repetitions. This gradual decrease likely stems from neuromuscular fatigue occurring in the nervous system (i.e., central fatigue) and working muscles (i.e., peripheral fatigue) (D. G. Allen, Lamb, & Westerblad, 2008; Sahlin, 1992; Taylor et al., 2016). However, the difference between conditions in the pattern of force production, namely, the differential rate of this decrease, likely stems from psychological causes. This is because neuromuscular fatigue impacts the working muscles but has limited effect on remote and rested muscle groups (Behm et al., 2021). Hence, the steeper slope in force production in the varied condition compared to the fixed condition should be attributed to psychological factors such as cognitive overload, changes in motivation, and/or mental fatigue (De Morree et al., 2012; Marcora & Staiano, 2010). Our results also suggest that off-task uncertainty, that is, the uncertainty regarding the moment-to-moment effort requirements on task-irrelevant muscles, plays a role in regulating effort allocation over time. Effort regulation is impacted by the prospective demands of the overall effort requirements and by how predictable the task environment is (even if predictability does not concern effort by the focal muscle group).

The pattern of force output in the varied condition could be described as a more pronounced all-out pattern of effort allocation (high start, rapid decline) compared to the pattern in the fixed condition. It is interesting to note that an all-out strategy may be (but does not have to be) devoid of planning, because it could emerge if an actor applies, at each point in time, the maximum possible level of effort, with no consideration for future effort demands. A flatter pattern, in contrast, requires moderation of effort in view of future demands, and thus involves planning, which may depend on executive resources (Braver, 2012; Morris & Ward, 2004). Perhaps consistent with this analysis, it has been found that children (more than adults) and people with intellectual impairment (compared to neuro-typical adults) tend to adopt all-out patterns of effort allocation in endurance-based activities (Micklewright et al., 2012; Sakalidis et al., 2021; Van Biesen et al., 2016). It is possible that in our studies uncertainty enhanced the use of the all-out strategy because it introduced cognitive demand that interfered with planning of effort.

More generally, it is possible that when people are certain about future task demands, they might prioritize long-over short-term performance. High certainty grants one the ability to avoid unnecessary waste of resources, while keeping up with certain performance standards, as future task performance is unthreatened by unexpected events. In contrast, because uncertainty suggests that future task performance might be interrupted by unexpected events, people might try to invest more resources at initial task performance, when they know that they still can do that.

Of note, participants in our studies were instructed to produce maximum MVC on each of the 20 repetitions. We think that a different pattern of results may have emerged had they been instructed to accumulate a maximum force over the 20 repetitions (for example, had they been told that on each one of the 20 repetitions they get a number of points that is equivalent to the %MVC they achieve, and that their goal is to earn maximum points). Most likely, this modified task would have produced a "stuck in the middle" effect, whereby people invest more effort at the beginning of a task and toward its end, and reduce effort in the middle (Emanuel, 2019; Emanuel et al., 2021, 2022). It would be interesting to examine, in future studies, how off-task uncertainty might affect the steepness of this pattern.

Future studies might also employ the current protocol with longer, endurance-based tasks, such as long-distance running, cycling or swimming. Would introducing off-task uncertainty cause runners, cyclists and swimmers to start with a higher pace, that would then decline

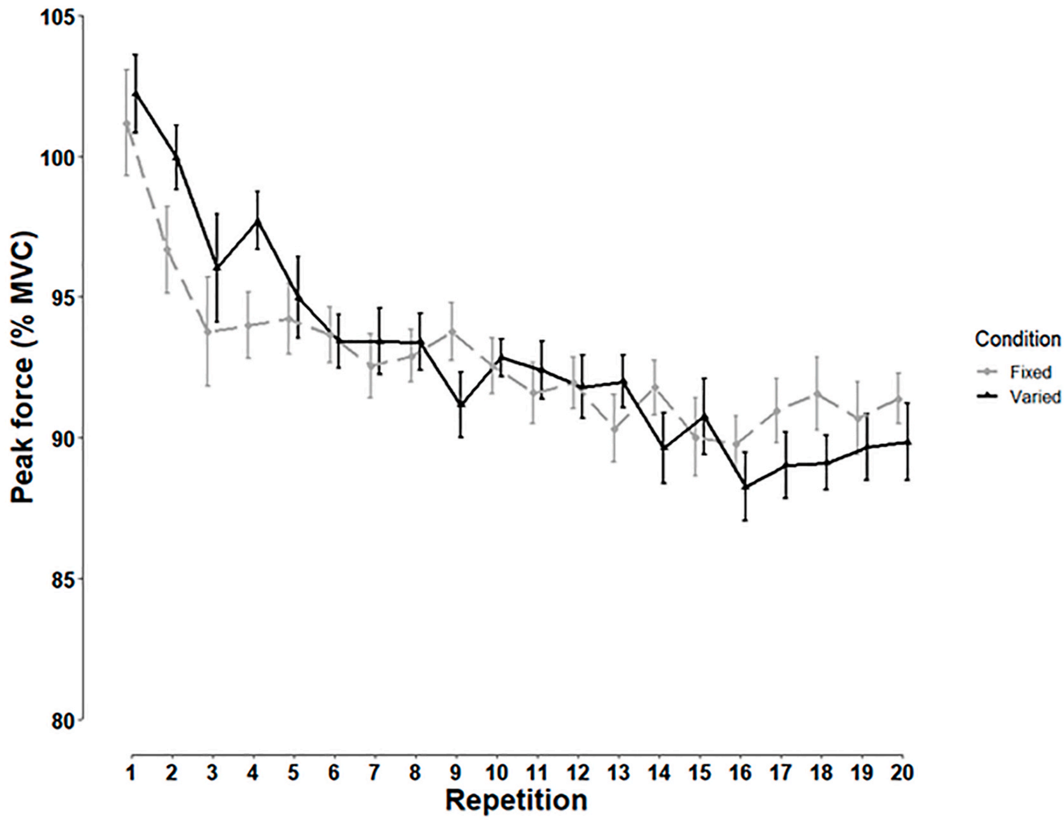

Figure 3. Force production over time in Experiment 2 in the fixed and varied conditions. The Y-axis represents peak force values of each repetition as the percent of the mean peak force from the pre-test measurement on that day for each participant. In the fixed (varied) condition, before each repetition participants produced with their non-dominant hand a target force of 60% of their MVC (in the fixed condition) or a force which was randomly drawn from a normal distribution with a mean of 60% of their MVC and an SD of 17 (in the varied condition).

at a faster rate? Outcomes from such projects might suggest, for example, that uncertainty might contribute to higher accumulated fatigue at the end of tasks due to a higher initial pace.

4. Conclusion

In two experiments, we found that physical effort decreased more steeply, but overall level of effort applied over time remained similar when uncertainty was introduced with respect to the trial-to-trial force demands on another group of muscles. This finding suggests that a pattern of steep decrease in force, which is traditionally attributed to fatigue, can be produced, at least partially, by off-task uncertainty, which concerns effort demand on muscles that are not directly involved in the focal task.

Author contributions

Aviv Emanuel, Israel Halperin, and Nira Liberman conceived the idea, Aviv Emanuel, Itai Har-Nir, and Idan Haklay collected the data, Aviv Emanuel formatted and analyzed the data, Aviv Emanuel, Israel Halperin, and Nira Liberman wrote the paper, Nira Liberman and Israel Halperin supervised the project.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared the complete data concerning this work via https://osf.io/wjc46/?view_only=6c7557557b744881ba9998af52f69a53.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.psychsport.2024.102618.

References

Allen, D. G., Lamb, G. D., & Westerblad, H. (2008). Skeletal muscle fatigue: Cellular mechanisms. *Physiological Reviews, 88*, 287–332.

Allen, E. J., Dechow, P. M., Pope, D. G., & Wu, G. (2016). Reference-dependent preferences: Evidence from marathon runners. *Management Science, 63*(6), 1657–1672. https://doi.org/10.1287/mnsc.2015.2417

Behm, D. G., Alizadeh, S., Hadjizedah Anvar, S., Hanlon, C., Ramsay, E., Mahmoud, M. M. I., Whitten, J., Fisher, J. P., Prieske, O., & Chaabene, H. (2021). Non-local muscle fatigue effects on muscle strength, power, and endurance in healthy individuals: A systematic review with meta-analysis. *Sports Medicine, 51*(9), 1893–1907.

Bliese, P. D., & Ployhart, R. E. (2002). Growth modeling using random coefficient models: Model building, testing, and illustrations. *Organizational Research Methods, 5*(4), 362–387. https://doi.org/10.1177/109442802237116

Braver, T. S. (2012). The variable nature of cognitive control: A dual mechanisms framework. *Trends in Cognitive Sciences, 16*(2), 106–113.

Cheema, A., & Bagchi, R. (2011). The effect of goal visualization on goal pursuit: Implications for consumers and managers. *Journal of Marketing, 75*(2), 109–123. https://doi.org/10.1509/jmkg.75.2.109

De Morree, H. M., Klein, C., & Marcora, S. M. (2012). Perception of effort reflects central motor command during movement execution. *Psychophysiology, 49*(9), 1242–1253.

Emanuel, A. (2019). Perceived impact as the underpinning mechanism of the end-spurt and U-shape pacing patterns. *Frontiers in Psychology, 10*. https://doi.org/10.3389/fpsyg.2019.01082

Emanuel, A., Herszage, J., Sharon, H., Liberman, N., & Censor, N. (2021). Inhibition of the supplementary motor area affects distribution of effort over time. *Cortex, 134*, 134–144.
Emanuel, A., Katzir, M., & Liberman, N. (2022). Why do people increase effort near a deadline? An opportunity-cost model of goal gradients. *Journal of Experimental Psychology: General*.
Gendolla, G. H., & Wright, R. A. (2009). Efort. In D. Sander, & K. R. Scherer (Eds.), *Oxford companion to the affective sciences* (pp. 134–135). New York: Oxford University Press.
Halperin, I., Aboodarda, S. J., Basset, F. A., Byrne, J. M., & Behm, D. G. (2014). Pacing strategies during repeated maximal voluntary contractions. *European Journal of Applied Physiology, 114*(7), 1413–1420. https://doi.org/10.1007/s00421-014-2872-3
Hanson, N. J., & Buckworth, J. (2015). The effect of endpoint knowledge on perceived exertion, affect, and attentional focus during self-paced running. *The Journal of Strength & Conditioning Research, 29*(4), 934–941.
Leyk, D., Gorges, W., Ridder, D., Wunderlich, M., Rüther, T., Sievert, A., & Essfeld, D. (2007). Hand-grip strength of young men, women and highly trained female athletes. *European Journal of Applied Physiology, 99*, 415–421.
Marcora, S. M., & Staiano, W. (2010). The limit to exercise tolerance in humans: Mind over muscle? *European Journal of Applied Physiology, 109*(4), 763–770. https://doi.org/10.1007/s00421-010-1418-6
McGibbon, K. E., Pyne, D. B., Shephard, M. E., & Thompson, K. G. (2018). Pacing in swimming: A systematic review. *Sports Medicine, 48*(7), 1621–1633. https://doi.org/10.1007/s40279-018-0901-9
Micklewright, D., Angus, C., Suddaby, J., St Clair Gibson, A., Sandercock, G., & Chinnasamy, C. (2012). Pacing strategy in schoolchildren differs with age and cognitive development. *Medicine & Science in Sports & Exercise, 44*(2), 362–369.
Morris, R., & Ward, G. (2004). *The cognitive psychology of planning*. Psychology Press.
Noakes, T. D. (2007). The central governor model of exercise regulation applied to the marathon. *Sports Medicine, 37*(4), 374–377.
Sahlin, K. (1992). Metabolic factors in fatigue. *Sports Medicine, 13*, 99–107.
Sakalidis, K. E., Burns, J., Van Biesen, D., Dreegia, W., & Hettinga, F. J. (2021). The impact of cognitive functions and intellectual impairment on pacing and performance in sports. *Psychology of Sport and Exercise, 52*, Article 101840.
Taylor, J. L., Amann, M., Duchateau, J., Meeusen, R., & Rice, C. L. (2016). Neural contributions to muscle fatigue: From the brain to the muscle and back again. *Medicine & Science in Sports & Exercise, 48*(11), 2294.
Tucker, R., Lambert, M. I., & Noakes, T. D. (2006). An analysis of pacing strategies during men's world-record performances in track athletics. *International Journal of Sports Physiology and Performance, 1*(3), 233–245. https://doi.org/10.1123/ijspp.1.3.233
Van Biesen, D., Hettinga, F. J., McCulloch, K., & Vanlandewijck, Y. (2016). Pacing profiles in competitive track races: Regulation of exercise intensity is related to cognitive ability. *Frontiers in Physiology, 7*, 624.
Wingfield, G., Marino, F., & Skein, M. (2018). The influence of knowledge of performance endpoint on pacing strategies, perception of effort, and neural activity during 30-km cycling time trials. *Physiological Reports, 6*(21), Article e13892.