How visual and proprioceptive feedback mediate the effect of monetary incentive on motor precision

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Abstract

This paper investigates the relationship between motor precision, visual feedback, and monetary incentives in 2 experiments. In both, participants exerted force via a hand dynamometer to maintain force production at identified levels while we manipulated the quality of visual feedback. In Experiment 1, monetary incentives improved motor performance only when visual feedback was provided. In Experiment 2, we simplified target representation by reducing the number of targets, making them easier to distinguish via proprioception and somatosensation. Under these conditions, incentives enhanced performance even without visual feedback. These findings suggest that while visual feedback is key to mediating motivational effects on fine motor control, incentives can also directly enhance performance when targets are easily represented through proprioceptive cues.

Keywords: Sensory Feedback; Motor Control; Incentives

1 Introduction

Daily activities demand precise control of force generation. As a real-world example, consider a waiter balancing a tray loaded with dishes. This individual must maintain fine gradation of force to sustain tray balance while navigating through a busy, dynamic environment. This kind of force generation clearly relies on monitoring of somatosensory and proprioceptive feedback (Whittier, Patrick, & Fling, 2023). Our waiter will be acutely aware of the position of his hand and the force created by the weight of the tray. However, he will also visually monitor his performance, and this is an example of how fine motor behaviour is also guided by visual feedback (Goodale & Milner, 1992; Milner & Goodale, 2008).

In the lab, results show that raw accuracy in force generation generally decreases as required force magnitude increases, but that visual feedback mitigates this pattern and improves accuracy (Limonta, Rampichini, Cè, & Esposito, 2015; Noble, Eng, & Boyd, 2013). When visual feedback is entirely removed, force tends to diminish and drift (Mayhew, Porcaro, Tecchio, & Bagshaw, 2017; Vaillancourt, Slifkin, & Newell, 2001; Abolins & Latash, 2022; Abolins, Ormanis, & Latash, 2023). Similarly, overall variability in force generation increases as a function of required force (Vaillancourt & Russell, 2002), but reduces when visual feedback is provided, stabilizing performance (Vaillancourt, Thulborn, & Corcos, 2003; Slifkin, Vaillancourt, & Newell, 2000; Baweja, Kennedy, Vu, Vaillancourt, & Christou, 2010).

Performance is also sensitive to motivational incentive, which wields significant influence over force generation and fine motor performance (Manohar et al., 2015;

Adkins, Gary, & Lee, 2021). The prospect of monetary reward potentiates participant willingness to engage in an action involving force generation (Klein-Flügge, Kennerley, Friston, & Bestmann, 2016; Apps, Grima, Manohar, & Husain, 2015; Croxson, Walton, O'Reilly, Behrens, & Rushworth, 2009; Le Bouc et al., 2016) and energizes force contraction (Zénon, Devesse, & Olivier, 2016; Pessiglione et al., 2007; Oudiette, Vinckier, Bioud, & Pessiglione, 2019). It also impacts the trade-off between force exertion and rest (Meyniel, Sergent, Rigoux, Daunizeau, & Pessiglione, 2013; Müller, Klein-Flügge, Manohar, Husain, & Apps, 2021). When the restaurant is busy and there is money to be earned, our waiter will maintain his performance despite increased pace and heavier loads.

Each of these influences on force generation – the effect of visual feedback and the effect of incentive motivation – have been individually investigated at considerable depth, but their interaction has been relatively underexplored. There are a range of possibilities here. At one extreme, the effect of incentive motivation on force generation may be strongly mediated by the monitoring of visual feedback. By this, the prospect of reward may act in large part by motivating individuals to track visual feedback regarding the accuracy and efficacy of performance so this can be used to optimize behaviour. At the other extreme is the possibility that the effect of motivation on motor performance is independent of visual feedback. This could mean that motivation acts directly to accentuate motor control, or that motivation influences how individuals use somatosensory and proprioceptive information to optimize their behaviour. When our waiter is motivated by monetary prospect to work harder, does this reflect increased consideration of the visual position and tilt of his tray? Or does he more carefully monitor proprioceptive information about his hand position and force exertion? If both, how much does his ability to improve performance rely on visual feedback on task performance?

We conducted 2 experiments to investigate this issue. Our general experimental paradigm draws inspiration from previous research investigating motor control and the impact of incentives on maximal force exertion (eg. Pessiglione et al., 2007). Participants were asked to exert force via a hand dynamometer to target levels that were defined as a percentage of maximum voluntary contraction. They were informed at the beginning of each trial that a cash reward could be earned for accurate task performance, and we manipulated the magnitude of this reward across trials (20¢ vs 1¢). We also independently manipulated the availability of visual feedback on performance accuracy. In some trials participants were provided continuous, online feedback about how closely their performance approached the target level of force generation. In other trials, this information was limited to the initial estimation of force generation, or to the later maintenance of force, or was absent altogether. Our aim was to assess how the impact of incentive motivation on force generation was influenced by change in the presence and quality of visual feedback.

To foreshadow, in Experiment 1 we find that when visual feedback is removed from our task, participants show no motivational benefit to task performance. In the confines of this experiment, the impact of motivation on fine force control appears entirely mediated by the visual feedback on performance accuracy. However, in Experiment 1 we employ a large range of target forces, and this may have made it difficult for participants to represent these targets in terms of proprioception and somatosensation. Experiment 2 was designed to determine if motivation would impact performance when there were fewer potential force targets, such that these might be better distinguished in terms of proprioception. This led to re-emergence of motivation effects when visual feedback was absent or limited in duration. Our results show that visual feedback plays a key mediating role in the effect of motivation on force generation, in particular when target performance is subtle and difficult to represent via proprioception alone.

2 Methods

2.1 Participants

Twenty-two participants (12 females, 10 males; mean age 24.3 years; range 20-30 years) gave informed consent before completing experiment 1 and a separate group of 22 subjects (12 females, 10 males; mean age 24.3; range 20-31) gave informed consent before completing experiment 2. The participants were all right-handed and naive to the purpose of the experiment. Two male participants were excluded from the analysis of experiment 1 and 2 participants, 1 male and 1 female, were excluded from the analysis of experiment 2. Three of these excluded participants commonly failed to respond, particularly in experimental conditions where earnings were reduced, resulting in force error and force variance that was more than 3 standard deviations from the group mean. The fourth participant consistently exerted force that was substantially over the target, suggesting inaccuracy in the calibration of maximum force that preceded experimental participation. Participants were paid based on performance, with pay varying between 5 and 15 euros in experiment 1 and between 10 and 21 euros in experiment 2. All gave informed written consent and the study procedure was approved by the local institutional review board of the University of Trento.

2.2 Apparatus and Stimuli

In both experiments, participants sat at approximately 60 cm from a computer monitor (VIEWPixx/EEG 22”; 1920x1080; 120 Hz) in a dimly illuminated room with their right hand laying over the table grasping a hand dynamometer. The dynamometer (HD-BTA Vernier) was used to record power grip force effort in Newtons (N) with an accuracy of ±0.6 N. This dynamometer is a strain-gauge-based isometric force sensor which amplifies force and converts it into a voltage signal. The voltage signal was transferred to an Arduino One through Vernier interface shield hardware and subsequently to an acquisition computer. The force signal was sampled at 50 Hz in experiment 1 and at 80 Hz in experiment 2. During the experiments, signals from this sensor were sent to MATLAB (The Mathworks Inc.) for visual real-time feedback of participant’s effort exertion. Feedback was updated at a frequency rate of 25 Hz in experiment 1 and 20 Hz in experiment 2. Presentation of visual stimuli and acquisition of behavioural data was accomplished using PsychToolBox (Brainard, 1997) and custom MATLAB scripts. Before beginning each experiment participants were requested to exert the most force they could on the dynamometer 3 times, each time for 3 s., with 10 s. of rest between each instance. The maximal voluntary contraction (MVC) was computed as the average of the highest peaks achieved in each of these trials.

Experiment 1 was designed to investigate how reward incentivization interacts with visual feedback during a task requiring force exertion and maintenance. The trial sequence is illustrated in Fig. 1A. Each experimental trial began with a cue indicating the incentive condition (20 cents or 1 cent) then a target force appeared, which was randomly selected from 5 possibilities and calculated as a percentage of MVC (38%, 46%, 54%, 62%, and 70%). Participants attempted to match this target force level with the hand dynamometer using a whole-hand power grip. For half of the trials, participants were presented with online visual feedback, for the other half they had to rely on their somatosensory inputs only. When visual information was present, feedback took the form of a stylized black thermometer that was displayed at the centre of an otherwise uniform dark grey background. The thermometer became increasingly red as force was exerted on the dynamometer and a green square on the thermometer indicated the target force output. When visual feedback was absent, the thermometer appeared but did not move.

Task performance lasted 3 s. and began with an auditory tone indicating the beginning of a 1 s. force estimation period, in which participants should adjust the force to the target value. A tone subsequently indicated the beginning of a 2 s. maintenance period and a final tone indicated the end of the trial. Experiment 1 took about 2 hours to complete and was composed of 15 practice trials followed by 300 experimental trials in 15 blocks, with breaks between blocks.

In each trial, participants received a percentage of the incentive value cued at the beginning of the trial, with the specific percentage determined by the quality of task performance. This was calculated based on a quadratic scoring rule computed across the 2 s. maintenance period of task performance. Participants were instructed that both overshoot and undershoot were penalized and were explicitly aware of the relationship between their performance and their pay.

As described below, results suggested that participants may have had difficulty representing or reproducing the large number of subtly differing force target values that were employed in Experiment 1. To test this, Experiment 2 employed only three force target values (35%, 50% and 65% of MVC). Experiment 2 additionally included two new feedback conditions designed to investigate the role of feedback in the control versus maintenance of force exertion. The total feedback (TF) and no feedback (NF) conditions described above were joined by early feedback (EF) and late feedback (LF) conditions. In the EF condition, force feedback was provided only for the first 1.5 seconds of task performance, then disappeared with the onset of the second tone. In the LF condition force feedback was provided 1.5 seconds after the beginning of performance and sustained for 2.5 s. until the end of the trial. As in Experiment 1, task performance began with an auditory tone indicating the need for force estimation, followed 1.5 s. later by a tone indicating the beginning of a 2.5 s. maintenance period before a final tone indicated the end of the trial.

Importantly, feedback in the LF condition was not a direct reflection of actual force, but rather reflected variance in performance from a normalized baseline established at the beginning of the feedback period. That is, the force recorded at the start of feedback was set in the visual feedback as equivalent to the current target force. This meant that force feedback always began at the target level, with subsequent deviation reflecting variance from the force magnitude established at the beginning of the feedback interval. This approach was adopted in order to provide participants with an accurate reflection of variance in their performance during the maintenance period without providing information regarding absolute accuracy.

As in Experiment 1, there were two incentive conditions in Experiment 2 (1 cent and 20 cents) that were cued at the beginning of each trial. An additional, concurrent cue indicated the type of feedback in the trial, such that participants could prepare for

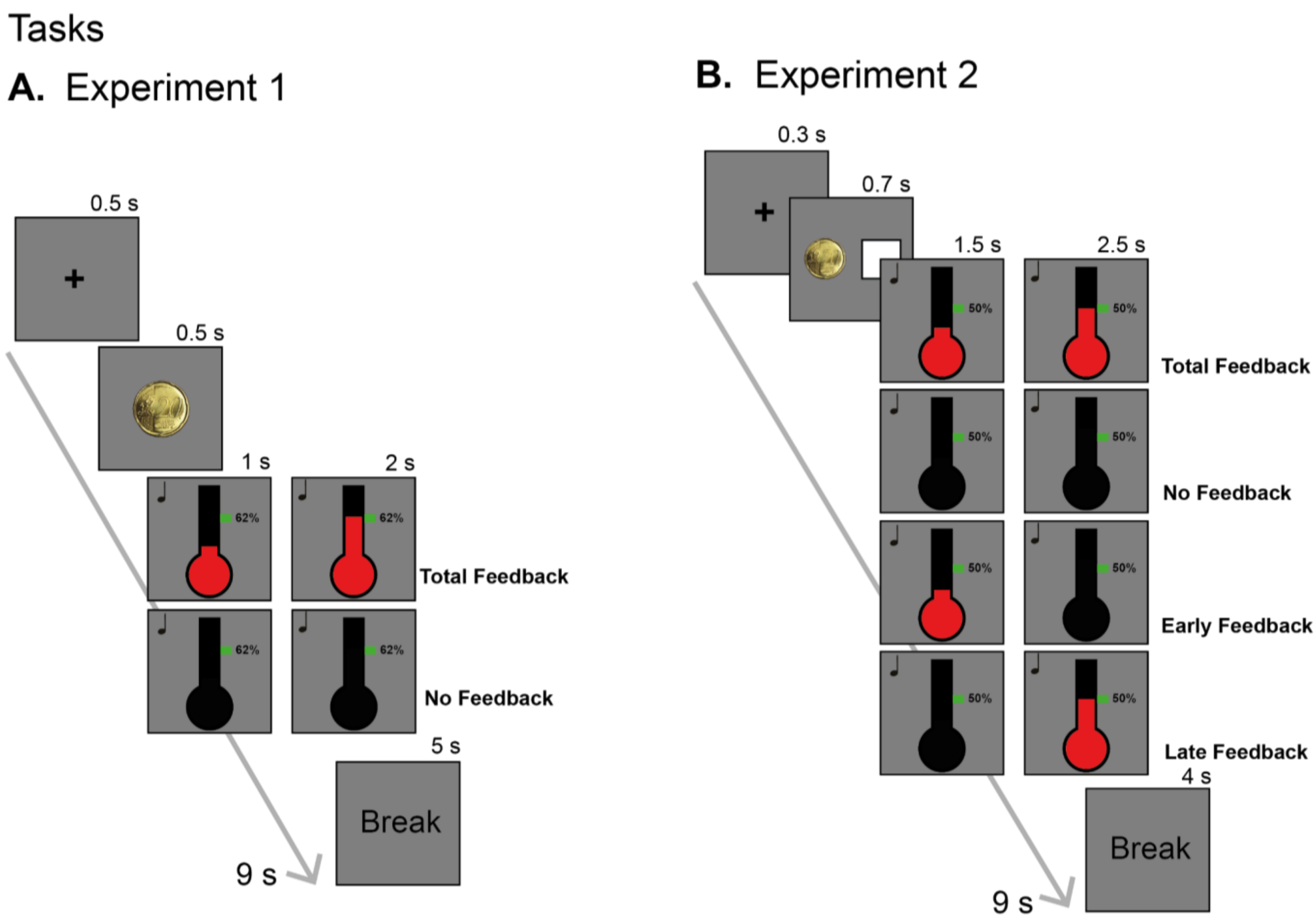

Figure 1: **Task schematics**. **A** Experiment 1. Each trial started with the presentation of a fixation cross (500 ms), followed by an image of the incentive that could be won in the trial (500 ms). An auditory stimulus subsequently identified the beginning of the trial and the feedback display appeared. The feedback, if present, was displayed as a red fluid in a stylized thermometer shape. The task lasted 3 seconds, 1 second of force estimation and 2 seconds of maintenance (both signalled by an auditory stimulus), followed by an invitation to relax the hand for 5 seconds. Each trial lasted 9 seconds in total. Participants received feedback during both force estimation and maintenance (Total feedback condition) or no feedback throughout the task (No Feedback). At the end of each block, participants were shown a message to relax and given information about the cumulative reward earned during that block. **B** Experiment 2. Each trial started with the presentation of a fixation cross for 300 ms, followed by the presentation of two cues (700 ms) that provided information about both feedback and incentive conditions. An auditory stimulus subsequently identified the beginning of the trial and the visual feedback, if present, appeared. Feedback was provided as in Experiment 1. The task lasted 4 seconds, 1.5 seconds of force estimation and 2.5 seconds of maintenance (both signalled by an auditory stimulus), followed by an invite to relax the hand for 4 seconds, for a total of 8 seconds per trial. In this experiment, two new feedback conditions were introduced: Early Feedback, in which feedback was present during force estimation only, and Late Feedback, in which feedback was present during force maintenance only. As in Experiment 1, information about the cumulative sum of reward earned during the block was provided at the end of the block.

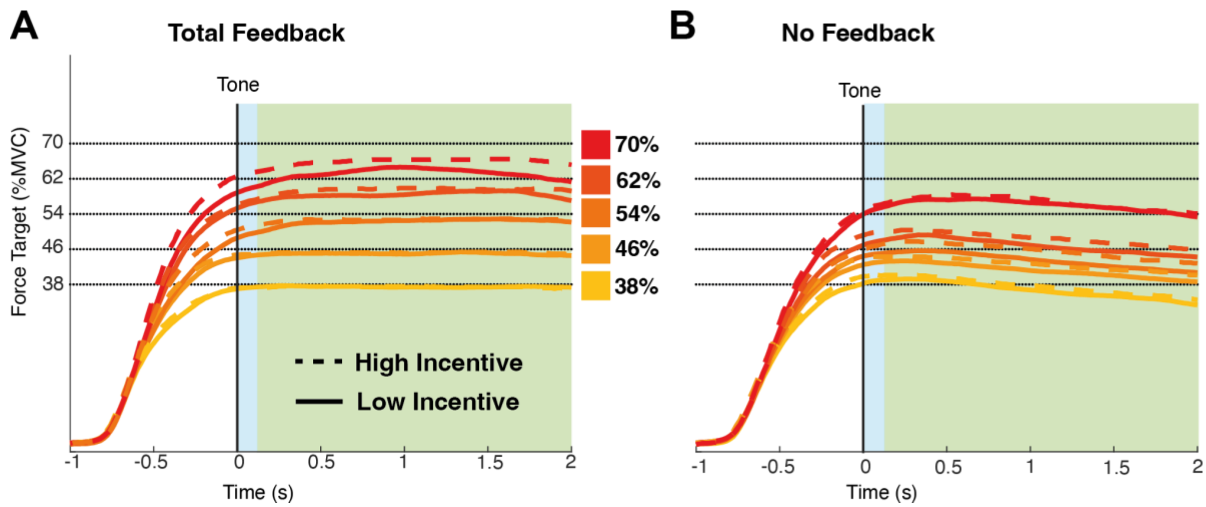

Figure 2: **Force estimation and maintenance in Experiment 1** Panels **A-B** show the average performance across participants in the total feedback and no feedback conditions. The interval highlighted in blue was defined as force estimation. The interval highlighted in green was defined as force maintenance.

the offset of feedback (in the EF condition) or the onset of feedback (in the LF condition). As illustrated in Figure 1B, an empty square indicated a NF trial; a fully black square indicated a TF trial; a square with the left side black indicated an EF trial; a square with the right side black indicated a LF trial. All conditions were randomized and counterbalanced across trials and the experiment was composed of 24 practice trials followed by 360 experimental trials divided into 15 blocks.

3 Experiment 1 - Data Analysis

Our main goal is to determine if incentives affect accuracy in force estimation and maintenance, and if this interacts with the availability of visual feedback information. We divide the analysis into two parts. First, we characterize force estimation as the average signed error from the target during 10 data-points after the end of the estimation period (See Fig. 2). We also calculate the consistency of this signal across trials. Second, we characterize force maintenance as the averaged error from the target during the maintenance period (See Fig. 2), additionally calculating variability in this signal within a trial, and the consistency of this signal across trials.

4 Results

4.1 Initial force estimation

Initial force estimation was computed as the average distance from the target of the 10 data points after the presentation of the auditory tone that indicated the end of the estimation period (Fig. 2). Force estimation was analyzed in a three-way mixed model analysis of variance (ANOVA) with factors for difficulty (5 levels: 38 - 70% MVC), incentive (2 levels: 1 cent vs. 20 cents), and feedback (2 levels: total feedback vs. no feedback). This identified significant main effects of difficulty ($F_{4,76} = 55.525$, $p < 0.001$) and feedback ($F_{1,19} = 13.999$, $p = 0.001$), alongside a trend toward a main effect of incentive ($F_{1,19} = 4.162$, $p = 0.055$). A significant interaction of feedback and difficulty emerged ($F_{4,76} = 22.568$, $p < 0.001$) alongside a critical 3-way interaction ($F_{4,76} = 2.829$, $p = 0.030$). The 3-way interaction was driven by a general increase in the effect of incentive with greater task difficulty, but only in the feedback condition. No other effects reached significance (difficulty * incentive: $F_{4,76} = 0.929$, $p = 0.452$; feedback * incentive: $F_{1,19} = 0.183$, $p = 0.673$).

These results are illustrated in Figure 3. To summarize, participants undershot the target and this tended to increase as difficulty increased. Performance was improved by feedback and by high incentives (See Fig. 3**A-B**). The effect of incentive was most pronounced in difficult trials when feedback was available (Fig. 3**C**), with this pattern absent when feedback was absent (Fig. 3D).

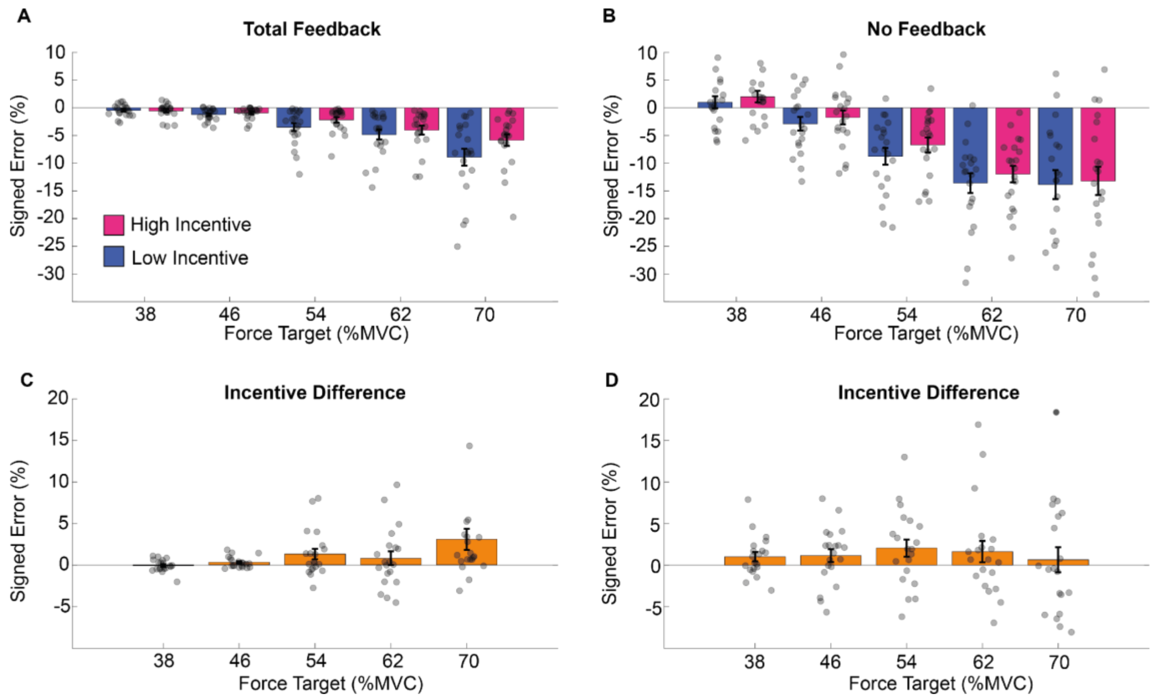

Figure 3: **Mean Force Estimation in Experiment 1** *Panels* **A-B** show the signed error during the force estimation period for the total feedback and the no feedback condition. Panels **C-D** show the difference between high and low incentive conditions for each target force level in the total feedback condition. In this and subsequent figures, each dot represents mean performance for a single participant and error bars represent standard error of the mean.

4.1.1 Consistency across trials

Consistency was computed as the standard deviation of the mean force estimation over trials within a participant. Consistency was analyzed in a three-way model analysis of variance (ANOVA) with factors for difficulty (5 levels: 38 - 70% MVC), incentive (2 levels: 1 cent vs. 20 cents), and feedback (2 levels: total feedback vs. no feedback). This identified significant main effects for difficulty ($F_{4,76} = 31.748$, $p < 0.001$) and feedback ($F_{1,19} = 82.572$, $p = 0.001$), alongside a trend toward an effect of incentive ($F_{1,19} = 4.137$, $p = 0.056$). A significant interaction of difficulty and feedback also emerged ($F_{4,76} = 2.756$, $p = 0.033$), as did an interaction of difficulty and incentive ($F_{4,76} = 3.118$, $p = 0.019$).

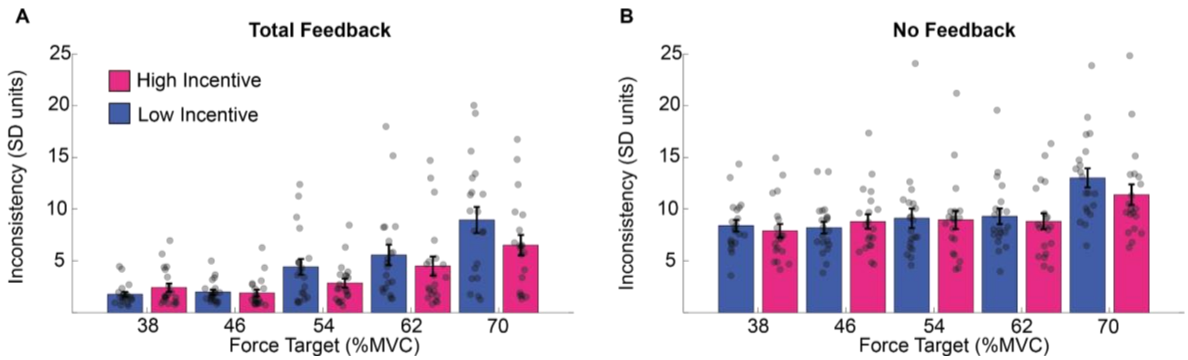

Figure 4: **Consistency of force estimation across trials in Experiment 1** *Panels* **A-B**. Performance consistency in estimating the force requested across trials for the total feedback condition and the no feedback condition. Consistency is represented in standard deviation units, thus smaller values reflect increased consistency.

No other effects reached significance (feedback*incentive: $F_{1,19} = 1.911$, $p = 0.182$; difficulty*feedback*incentive: $F_{4,76} = 1.014$, $p = 0.405$).

These results are illustrated in Figure 4. Force estimation was more consistent when feedback was present, and consistency decreased as difficulty increased. High incentives increased participants' consistency, especially when difficulty was high, but this pattern was not reliably sensitive to the manipulation of feedback.

4.2 Sustained Force Maintenance

Sustained force maintenance was computed as the average distance from the target of the data points after the end of the estimation period until the end of the trial (See Fig. 2). Sustained force was analyzed in a three-way mixed model analysis of variance (ANOVA) with factors for difficulty (5 levels: 38 - 70% MVC), incentive (2 levels: 1 cent vs. 20 cents), and feedback (2 levels: total feedback vs. no feedback). This identified all three main effects (difficulty: $F_{4,76} = 43.876$, $p < 0.001$; feedback: $F_{1,19} = 46.662$, $p < 0.001$; incentive: $F_{1,19} = 4.579$, $p = 0.0455$). An interaction between

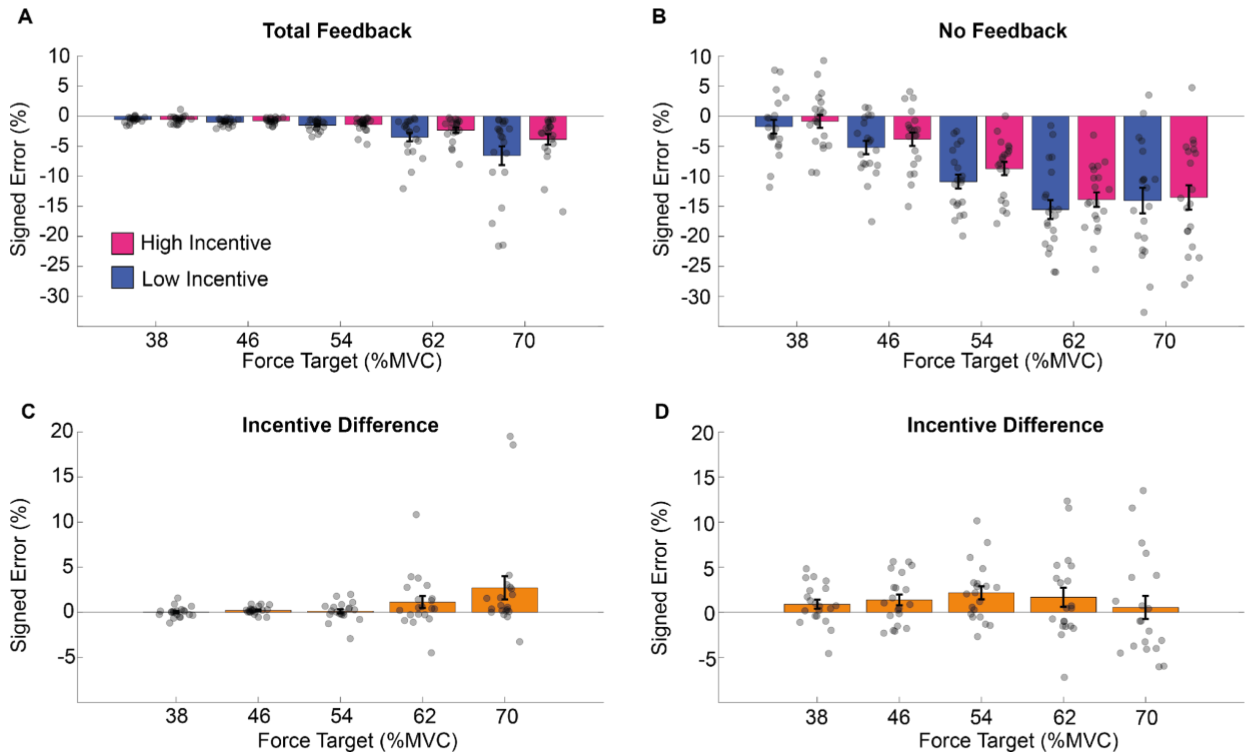

Figure 5: **Mean Force maintenance in Experiment 1** Panel **A-B.** shows the mean of the error from the target (Y-axis) during the force maintenance period in the total feedback and during the no feedback, at each force level (X-axis) and per incentive condition. Force error was defined as the difference at each time point between the observed force level and the current target. Positive values therefore reflects performance overshoot, and negative values undershoot. Panel **C** and **D** show the difference between high and low incentive, per force and feedback conditions.

difficulty and feedback also emerged ($F_{4,76} = 25.59$, $p < 0.001$) as did the 3-way interaction ($F_{4,76} = 4.844$, $p = 0.001$). No other effects reached significance (difficulty * incentive: $F_{4,76} = 0.8313$, $p = 0.213$; feedback * incentive: $F_{1,19} = 1.657$, $p = 0.213$).

These results are illustrated in Figure 5. Error increased with difficulty, but was reduced by visual feedback and incentive (Fig. 5**A-B**). The effect of incentive was most pronounced in difficult trials when feedback was provided (Fig. 5**C**), but this pattern did not emerge when feedback was absent (Fig. 5D).

4.2.1 Deviation within trials

Deviation was computed as the standard deviation of the force exerted during the maintenance period. Before calculating the standard deviation, exertion data was detrended to remove the linear drift in performance over the course of the trial. A higher standard deviation represents higher variability during the exertion. Deviation was analyzed in a three-way model analysis of variance (ANOVA) with factors for difficulty (5 levels: 38 - 70% MVC), incentive (2 levels: 1 cent vs. 20 cents), and feedback (2 levels: total feedback vs. no feedback). This identified significant main effects of difficulty ($F_{4,76} = 23.149$, $p < 0.001$) and feedback ($F_{1,19} = 16.764$, $p < 0.001$), alongside a trend toward an effect of incentive ($F_{1,19} = 3.732$, $p = 0.068$). The interaction of feedback and difficulty was significant ($F_{4,76} = 8.617$, $p < 0.001$), as was the interaction of difficulty by incentive ($F_{4,76} = 2.972$, $p = 0.024$). No other effects reached significance (feedback*incentive: $F_{1,19} = 3.267$, $p = 0.865$; difficulty*feedback*incentive: $F_{4,76} = 1.768$, $p = 0.143$).

These results are illustrated in Figure 6. Deviation increased with task difficulty, but was reduced by visual feedback and incentives (Fig. 6). The impact of incentive was greatest when the task was most difficult. While this effect of incentive appears larger in the feedback condition, this was not statistically reliable.

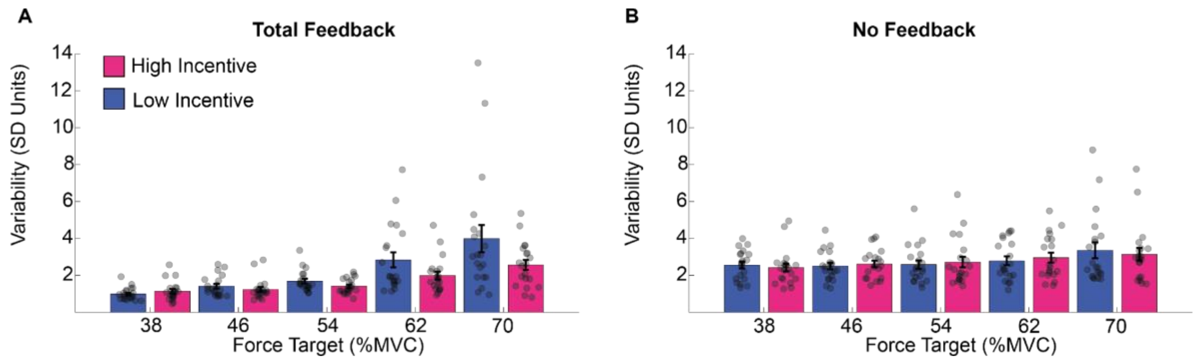

Figure 6: **Deviation from the target in Experiment 1** Panel **A-B** show the averaged standard deviation within trials for the total feedback condition , and the no feedback condition , per force (x-axis) and incentive condition. We averaged the standard error of force across time points in the force maintenance period (y-axis).

4.2.2 Consistency across trials

Consistency was computed as the standard deviation of the mean force exertion over trials within each participant. A higher standard deviation represents low consistency over trials. Consistency was analyzed in a three-way model analysis of variance (ANOVA) with factors difficulty (5 levels: 38 - 70% MVC), incentive (2 levels: 1 cent vs. 20 cents), and feedback (2 levels: total feedback vs. no feedback). This identified main effects of difficulty ($F_{4,76} = 16.707$, $p < 0.001$) and feedback ($F_{1,19} = 111.66$, $p = 0.001$). The difficulty by feedback interaction was also significant ($F_{4,76} = 4.718$, $p = 0.001$). No other effects reached significance (incentive: $F_{1,19} = 0.397$, $p = 0.535$; difficulty*incentive: $F_{4,76} = 1.51$, $p = 0.207$; feedback*incentive: $F_{1,19} = 1.001$, $p = 0.329$; difficulty*feedback*incentive: $F_{4,76} = 1.196$, $p = 0.319$).

These results are illustrated in Figure 7. Force maintenance became less consistent as difficulty increased, and this was acute in the feedback condition. Incentive had no reliable impact on any pattern in this data.

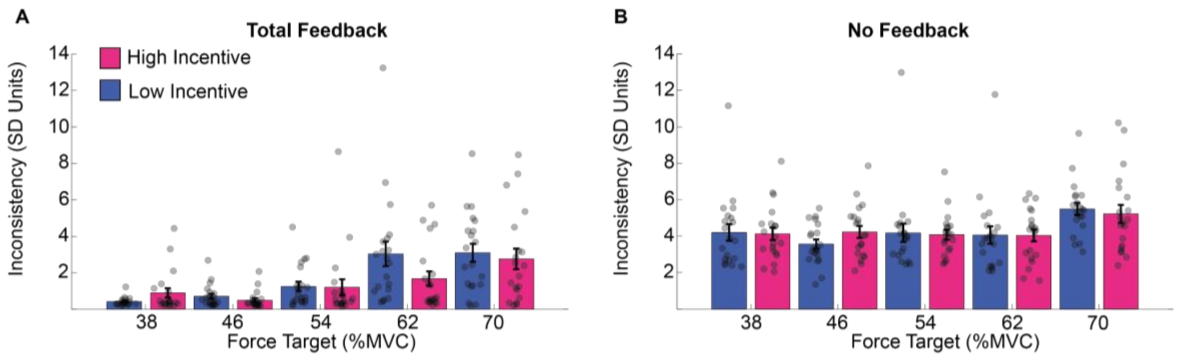

Figure 7: **Consistency of force estimation in Experiment 1** Panel **A-B** shows the results of the standard deviation of the mean exertion across trials (y-axis) during the total feedback condition and the no feedback condition, per force (x-axis) and incentive condition.

4.3 Summary of results from Experiment 1

These results suggest that visual feedback is necessary in order for incentive motivation to impact force generation. However, the task we employed in Experiment 1 involved five difficulty levels, and one possibility is that participants had trouble representing the fine gradiation of force that defined each target. As a result, participants may have relied more strongly on visual feedback in this experiment than would have been the case if target force levels were more limited in scope, and therefore easier to distinguish and represent based on somatosensory and proprioceptive feedback.

Experiment 1 also left unclear exactly when motivated use of visual feedback could be used to improve performance. That is, in our task participants prepare an action, implement this action, and then maintain force over a duration. The role of visual feedback in mediating motivated performance could vary across these stages of action implementation and maintenance.

We conducted a second experiment to address these issues. Experiment 2 was broadly similar to Experiment 1, with two changes. First, we reduced the number of force targets to 3, such that each target was more clearly distinguished from the others and therefore possibly easier to represent and monitor based solely on proprioceptive and somatosensory feedback. Second, we introduced two new feedback conditions. In the LF condition, force feedback was provided only during sustained force maintenance. This meant that participants had to use a somatosensory representation of the force target during initial force estimation, but could use visual feedback to monitor the consistency of their performance during each trial. In contrast, in the EF condition, force feedback was provided only until the end of the estimation period. Participants could therefore use the visual feedback to achieve target performance, but had to rely solely on somatosensory feedback during sustained force maintenance. These additional conditions allowed us to identify precisely how visual feedback mediates the impact of motivation on force control.

5 Experiment 2

6 Data Analysis

As in experiment 1, we divided the analysis into two parts. First, we characterise force estimation as the averaged signed error from the target during 10 data-points after the end of the estimation period (Fig. 8). We additionally calculate the consistency of this signal across trials. Second, we characterise force maintenance as the average error from the target during the maintenance period (Fig. 8), also calculating the deviation of this signal within a trial and the consistency of this signal across trials.

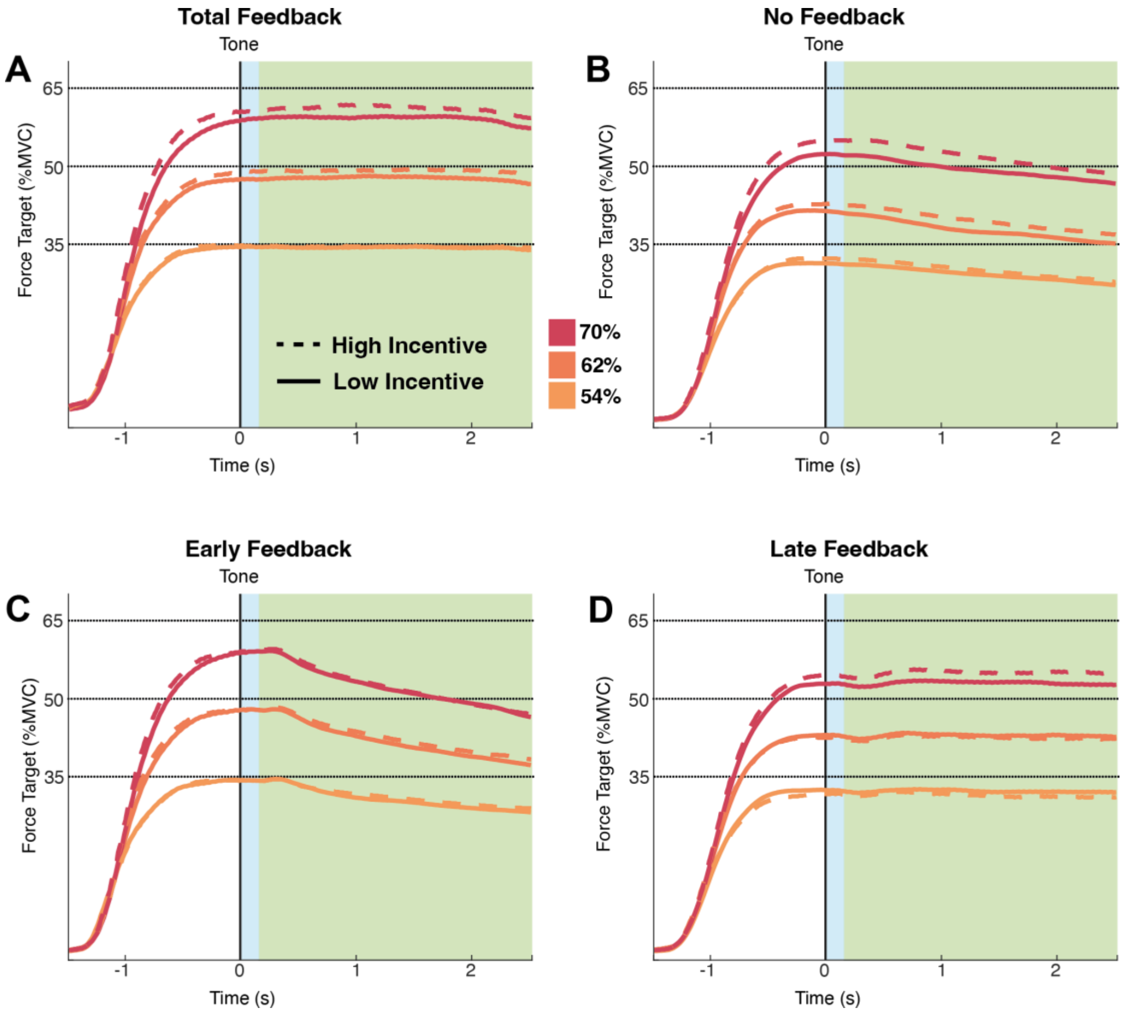

Figure 8: **Force estimation and maintenance in Experiment 2** Panels **A-B** show the average performance across participants in the feedback and no feedback. Panels **C-D** show the average performance across participants in the early feedback and late feedback conditions. The section highlighted in blue was selected as the force estimation interval. The section highlighted in green was selected as the force maintenance interval.

7 Results

7.1 Initial force estimation

Initial force estimation was computed as the average distance from the target of the 10 data points after the presentation of the auditory tone indicating the end of the estimation period (See Fig. 8). Force estimation was analyzed in a three-way mixed model ANOVA with factors for difficulty (3 levels), feedback (4 levels) and incentive (2 levels). The three main effects were significant (difficulty: $F_{2,38} = 18.328$, $p <$

0.001; feedback: $F_{3,57} = 19.349$, $p < 0.001$; incentive: $F_{1,19} = 4.459$, $p = 0.048$), as were all two-way interactions (difficulty*feedback: $F_{6,114} = 9.253$, $p < 0.001$; difficulty*incentive: $F_{2,38} = 5.899$, $p = 0.005$; feedback*incentive: $F_{6,14} = 3.29$, $p = 0.027$) but the three-way interaction was not significant ($F_{6,114} = 0.789$, $p = 0.579$).

The results are illustrated in Figure 9. As in the previous experiment, participants underestimated the target and tended to undershoot more as difficulty increased (See Fig. 9 **A-B-C-D**). Error was reduced by incentive and reliably varied across the feedback conditions. The effect of incentive increased as a function of task difficulty (See Fig. 9 **E-F-G-H**). This emerged across all feedback conditions, but the magnitude of the effect reliably varied as a function of feedback type, and was largest in the NF and LF conditions.

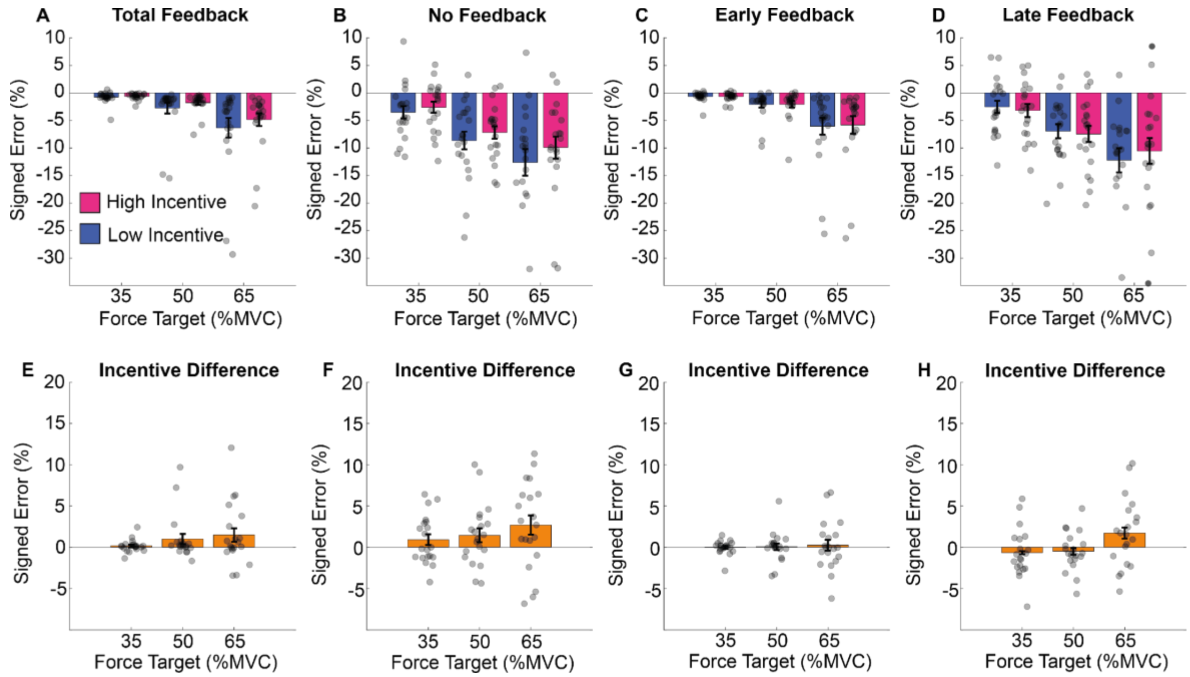

Figure 9: **Mean Force Estimation in Experiment 2** Panels **A-B-C-D** show the mean error from the target (Y-axis) during the estimation period in the four feedback conditions (4 panels), at each force level (X-axis) and per incentive condition. Panels **E-F-G-H** shows the difference between high and low incentive, per force and feedback conditions.

7.1.1 Consistency across trials

Consistency was computed as the standard deviation of the mean force estimation over trials within a participant. It was analyzed in a three-way mixed model ANOVA with factors for difficulty (3 levels), feedback (4 levels) and incentive (2 levels). This identified main effects of difficulty ($F_{2,38} = 80.158$, $p < 0.001$) and feedback ($F_{3,57} = 78.741$, $p < 0.001$). No other effect reached significance (incentive: $F_{1,19} = 1.639$, $p = 0.215$; difficulty*feedback: $F_{6,114} = 0.747$, $p = 0.612$; difficulty*incentive: $F_{2,38} = 0.12$, $p = 0.887$; feedback*incentive: $F_{3,57} = 0.28$, $p = 0.839$; difficulty*feedback*incentive: $F_{6,114} = 1.645$, $p = 0.141$).

These results are illustrated in Figure 10. Consistency decreased as a function of increasing difficulty, and was poor in conditions where feedback was absent (NF) or late (LF). Incentive had no reliable impact on any pattern in this data.

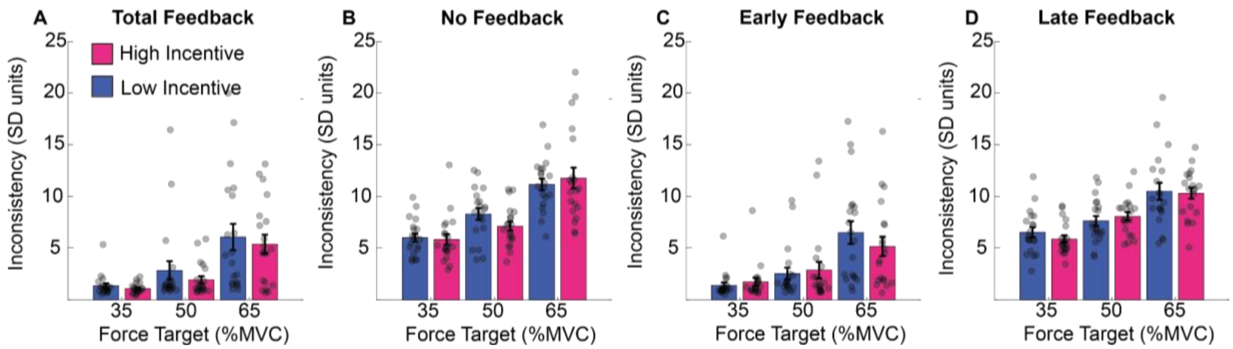

Figure 10: **Consistency of Force estimation in Experiment 2** Panels **A-B-C-D** show the mean of the error from the target (Y-axis) during the force maintenance period the different feedback conditions (four panels), at each force level (X- axis) and per incentive condition. Force error was defined as the averaged difference at each time point between the observed force level and the current target.

7.2 Sustained Force Maintenance

Sustained force maintenance was computed as the average distance from the target of the data points after the end of the estimation period until the end of the trial. It was analyzed in a three-way mixed model ANOVA with factors for difficulty (3 levels), feedback (4 levels) and incentive (2 levels). The three main effects were significant (difficulty: $F_{2,38} = 33.362$, $p< 0.001$; feedback: $F_{3,57} = 31.554$, $p < 0.001$; incentive: $F_{1,19} = 5.589$, $p = 0.028$). The interaction of difficulty by feedback was also significant ($F_{6,114} = 14.081$, $p < 0.001$), as was the interaction of difficulty and incentive ($F_{2,38} = 7.001$, $p = 0.002$). No other effect reached significance (difficulty*feedback*incentive: $F_{6,114}$ $= 1.734$, $p = 0.119$; feedback*incentive: $F_{3,57} = 2.63$, $p = 0.058$).

These results are illustrated in Figure 11. Participant error increased with difficulty (See Fig. 11 **A-B-C-D**), but performance improved as a function of both feedback and incentive (See Fig. 11 **A-B-C-D** for the effect of feedback and panels **E-F-G-H** for the effect of incentive). The effect of incentive increased as a function of difficulty (Fig. 11 **E-F-G-H**). This emerged similarly across feedback conditions.

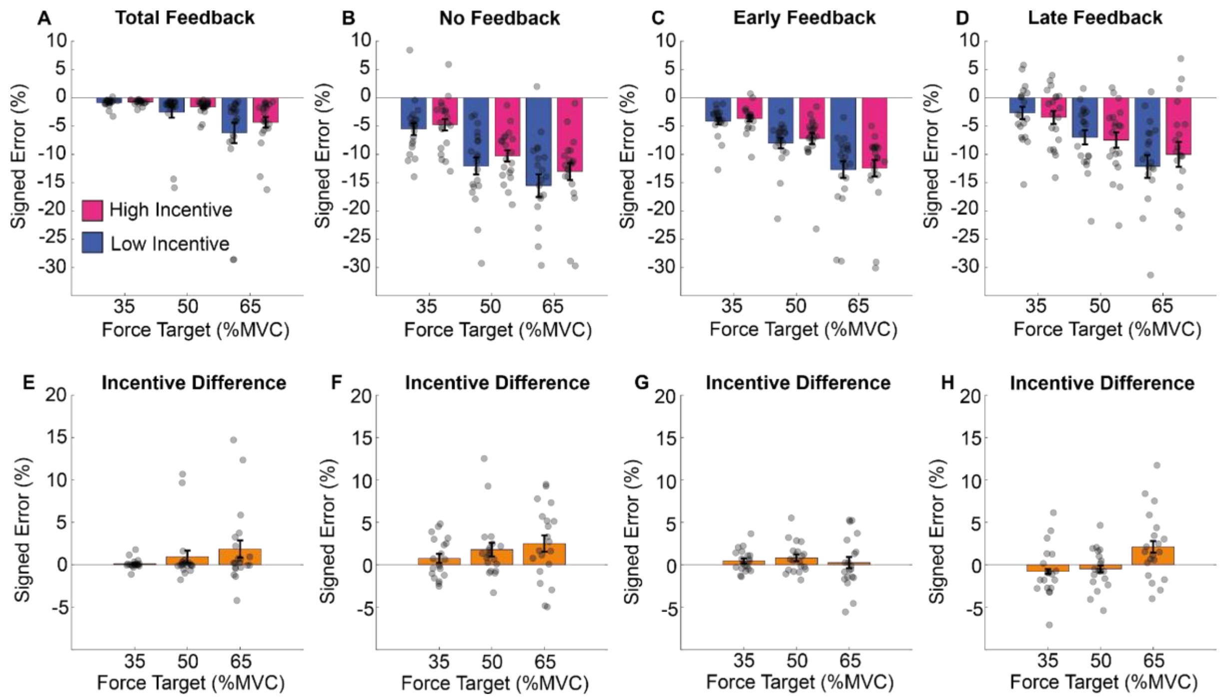

Figure 11: **Error from the target in Experiment 2** Panels **A-B-C-D** shows for the total feedback (left panels) and for the no feedback (right panels) conditions, at each force level (X-axis) and per incentive condition the mean of the error from the target (Y-axis) during the force maintenance period. Force error was defined as the difference at each time point between observed force level and the current target. The lower panel shows the difference between high and low incentive, per force and feedback conditions.

7.2.1 Deviation within trials

Deviation was computed as the standard deviation of the force exerted during the maintenance period. Before performing the standard deviation, exertion data was detrended to remove the linear drift in performance. A higher standard deviation represents higher variability during the exertion. Deviation was analyzed in a three-way mixed model ANOVA with factors for difficulty (3 levels), feedback (4 levels) and incentive (2 levels). The three main effects were significant (difficulty: $F_{2,38}$ = 94.012, $p < 0.001$; feedback: $F_{3,57}$ = 15.44, $p < 0.001$; incentive: $F_{1,19}$ = 8.479, p = 0.008).

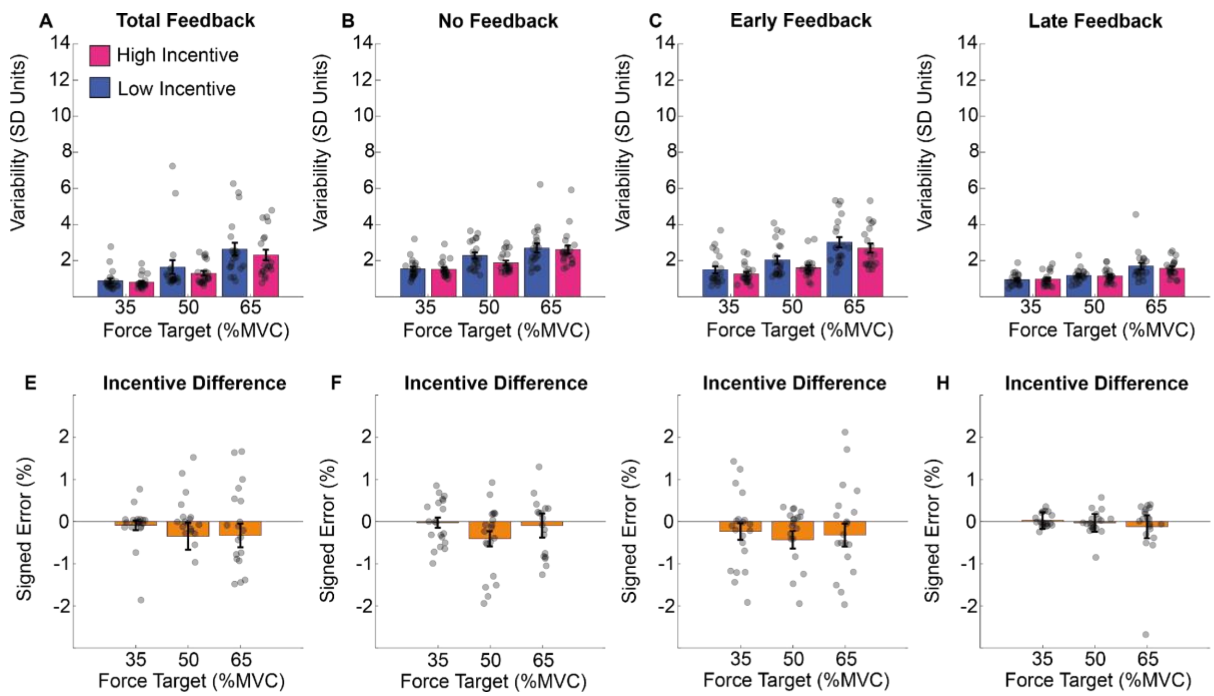

Figure 12: **Deviation from the target in Experiment 2** Panels **A-B-C-D** shows the averaged standard deviation within trials (y-axis) for the different feedback (four panels), force (x-axis) and incentive conditions. Panels **E-F- G-H** show the difference between high and low incentive, per force and feedback conditions.

Only the difficulty by feedback interaction was significant ($F_{6,114}$: 4.585, $p < 0.001$). No other effect reached significance (difficulty*incentive: $F_{2,38} = 1.597$; feedback*incentive: $F_{3,57} = 0.795$, $p = 0.501$; difficulty*feedback*incentive: $F_{6,114} = 0.252$, $p = 0.957$).

These results are illustrated in Figure 12. Participants' deviation from the target increased with task difficulty (Fig. 12**A-B-C-D**). Error reduced as a function of feedback type (LF and TF; Fig. 12**A-B-C-D**) and incentive (Fig. 12**E-F-G-H**). The impact of incentive did not vary as a function of task difficulty or feedback type.

7.2.2 Consistency across trials

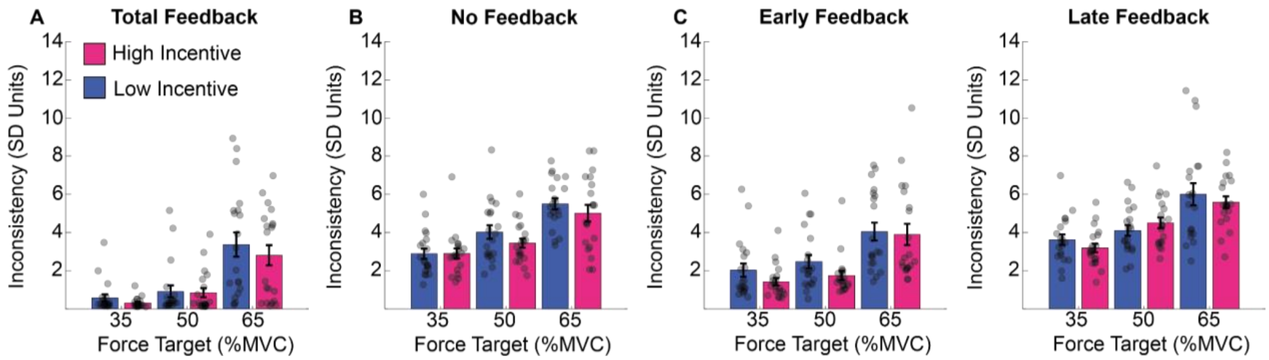

Figure 13: **Force consistency in Experiment 2** Panels **A-B-C-D** show the results of the standard deviation across trials for the total feedback condition (left panel), for the no feedback condition (right panel), per force and incentive condition. Standard error was computed on the mean force across time points in the force maintenance period.

Consistency was computed as the standard deviation of the mean force exertion over trials within a participant. It was analysed in a three-way mixed model ANOVA with factors for difficulty (3 levels), feedback (4 levels) and incentive (2 levels). The three-way mixed model ANOVA identified main effects of difficulty ($F_{2,38} = 78.958$, $p < 0.001$) and feedback ($F_{3,57} = 59.625$, $p = 0.001$) alongside a trend toward an effect of incentive ($F_{1,19} = 867$ $p = 0.064$). No other effects reached significance (difficulty*feedback: $F_{6,114} = 0.611$, p = 0.72; difficulty*incentive: $F_{2,38} = 0.189$, $p = 0.828$; feedback*incentive: $F_{3,57} = 0.352$, $p = 0.787$; difficulty*feedback*incentive: $F_{6,114} = 0.914$, $p = 0.486$).

These results are illustrated in Figure 13. Performance was more consistent when feedback was present (ie. TF and EF conditions), but degraded as difficulty increased. There was no impact of incentive on any pattern in this data.

7.3 Summary of Experiment 2

Results from Experiment 2 show a consistent effect of incentive on motor precision, regardless of the availability or quality of visual feedback. This suggests that the simplification of force targets adopted in Experiment 2 allowed participants to represent targets based solely on somatosensory and proprioceptive information. As such, they were able to monitor this information and optimize behaviour in high incentive conditions.

8 Discussion

Achieving precise motor control necessitates the integration of sensory input with internal representation to execute movement plans effectively (Cappadocia, Monaco, Chen, Blohm, & Crawford, 2017; Velji-Ibrahim, Crawford, Cattaneo, & Monaco, 2022). Subsequently, newly generated sensory feedback fine-tunes movement online (Crevecoeur, Cluff, & Scott, 2014; Turella, Rumiati, & Lingnau, 2020), with visual and proprioceptive information playing pivotal roles in this process (Sartin, Ranzini, Scarpazza, & Monaco, 2022; Monaco et al., 2010; Filimon, Nelson, Huang, & Sereno, 2009; Monaco et al., 2006). The two experiments reported here demonstrate the important role of visual feedback in mediating the effect of motivation on force generation accuracy and precision. In Experiment 1, we found that the impact of incentive motivation was entirely contingent on the provision of visual performance feedback. In Experiment 2, where performance targets were easier to distinguish from proprioceptive and somatosensory feedback, the benefit of motivation emerged in both total feedback and no feedback conditions.

We interpret this as evidence that motivation can impact difficult, fine motor performance even when visual performance feedback is not available. This may occur through a direct impact that decreases noise in the motor system, or through an indirect influence on participant monitoring of proprioceptive and somatosensory performance feedback.

8.1 Effect of Visual Feedback and Task Difficulty

Consistent with previous literature (Limonta et al., 2015; Noble et al., 2013; Vaillancourt et al., 2003; Slifkin et al., 2000; Baweja et al., 2010), our results underscore the critical role of visual feedback in monitoring force control accuracy and reducing variability, particularly in circumstances where target performance is subtle. Additionally, our analyses unveil a significant impact of task difficulty on force production, with increased demands leading to greater variability and deviations from the target. Returning to the example described in the introduction, our waiter is in a situation where force targets vary as a function of what drinks have been placed on the tray, and of the physics of the waiters' navigation through the restaurant. Under these circumstances, he will struggle to maintain balance and control of his tray without visual feedback.

8.2 Roles of feedback in force estimation and maintenance

In our second experiment, we introduced two novel feedback conditions—Early Feedback and Late Feedback— these conditions allowed us to compare the distinct effects of feedback on force estimation and force maintenance. In the Early Feedback condition, participants received feedback during the force estimation phase but not during the force maintenance phase. Participants' force estimation performance mirrored that observed in the feedback condition. However, once the feedback was withdrawn during the maintenance phase, the motor decay and the effect of incentives on performance did not significantly differ from the no feedback condition. Conversely, in the Late Feedback condition, participants received no feedback during the force estimation phase, relying entirely on their internal representation of the target force. Feedback was then introduced during the maintenance period. Here, participants' estimation resembled that of the no feedback condition. However, once feedback was introduced during the maintenance phase, performance mirrored the one observed in the feedback condition, with participants demonstrating reduced variability.

8.3 Interaction with Monetary Incentives

Incentives influence force production and this is evident in its ability to boost motivation, stimulate robust muscle contractions, and influence the exertion/rest trade-off (Klein-Flügge et al., 2016; Croxson et al., 2009; Le Bouc et al., 2016; Zénon et al., 2016; Pessiglione et al., 2007; Oudiette et al., 2019; Meyniel et al., 2013; Müller et al., 2021). Expanding on these findings, our study delved into the role of incentives in fine motor control. We observed an interaction between monetary incentives and task difficulty that particularly affects force accuracy and variability. While incentives positively impacted force control accuracy across all difficulty levels, this effect was most pronounced under high task difficulty. Participants demonstrated enhanced accuracy and reduced variability in force production when motivated by higher monetary incentives. This suggests that incentives play a crucial role in reducing errors in force production, especially when the task demands are high. In easier conditions, the motor system might be able to perform adequately without a strong motivational push. However, when the task becomes more challenging and errors become more likely, incentives appear to act as a facilitator, promoting greater focus, enhanced accuracy, and reduced variability in force production (Codol, Holland, Manohar, & Galea, 2020).

8.4 Role of Incentives in Feedback Modulation

Crucially, our findings indicate that the influence of incentives on force control depends on the ability to reliably monitor performance. In Experiment 1, incentives exerted a strong effect on force accuracy and consistency, especially under high difficulty. However, when visual feedback was absent, this effect disappeared. This suggests that incentive effects on motor precision were mediated by the availability of reliable visual feedback (Sporn, Chen, & Galea, 2022; Codol et al., 2023).

The second experiment presented a contrasting scenario. Here, participants formed a clear internal representation of the target force without relying on visual feedback. Interestingly, even in the absence of visual feedback, incentives continued to influence motor precision, particularly in terms of force estimation. This suggests that when a clear internal representation exists, incentives can exert a more direct effect on the motor control system itself, potentially influencing initial force generation and estimation before sensory feedback comes into play.

As noted above, the effect of motivation on performance in the absence of visual feedback could reflect a direct influence on the motor signal itself, to reduce internal noise in this system, or could act through a potentiation of how proprioceptive and somatosensory feedback is monitored by the participant. Our results show that, when visual feedback is absent, incentives have a particular impact on initial force estimation rather than force maintenance, and this is consistent with the idea of a direct effect on motor control. However, it is also likely that enhanced monitoring of proprioceptive and somatosensory feedback plays a role here, and identifying the precise involvement of each mechanism will require further experimentation.

In summary, our results demonstrate that motivational effects on fine motor control rely strongly on enhanced monitoring of visual feedback. This is the case in the common scenario where performance targets differ subtly, and are therefore difficult to represent in terms of proprioception and somatosensation. However, when targets are more easily distinguished in these terms, motivation will benefit performance even in the absence of visual feedback. This was further clarified in the second experiment with the introduction of two feedback conditions where feedback was manipulated in either the force estimation or the force maintenance. Visual feedback therefore plays an important role in mediating motivational effects on fine motor performance, but these effects can be instantiated more directly when levels of target performance are unambiguous and easily represented.

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