

VISUAL FEEDBACK IMPROVES THE EFFICIENCY OF
ANTICIPATORY FORCE CONTROL EVEN WHEN OBJECT
PROPERTIES ARE NOT SALIENT

by

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Object Properties Are Not Salient

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Anticipatory force control is the ability to plan the amount of force needed to successfully manipulate an object and is known to predominantly rely on two key aspects: sensorimotor memories derived from previous experience with the same or similar object and visual feedback of object properties (*e.g.*, size, texture, density). However, visual feedback does not always provide congruent information about an object's properties. In such instances, it has been assumed that subjects predominantly anticipate forces through learned experience with the object (*i.e.*, sensorimotor memory). I question whether anticipatory force control that relies on sensorimotor memories is aided by visual feedback of the hand and of the object, even when these visual cues are incongruent with an underlying key property. To study the contribution of visual feedback for planning object manipulation when it is incongruent with a key property of the object, we manipulated the availability of visual feedback as subjects learned to lift and minimize tilt of a symmetrical object with a hidden uneven mass distribution (N=48). Participants had to generate a torque anticipatorily at lift onset to successfully minimize tilt of the object. The results of this study support the hypothesis that even when visual feedback cues are incongruent with a key property of an object, the availability of visual feedback helps access the sensorimotor memories needed to anticipate the forces required to successfully manipulate an object.

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Introduction

Anticipatory force control is the ability to plan the amount of force needed to successfully manipulate an object. This involves pre-setting the grip and lift forces before contact onset with the object, where grip force is the normal force of the digits on the object surface and lift force is the vertical force that lifts the object. Anticipatory force control is known to predominantly rely on two key aspects: sensorimotor memories and visual feedback of an object's properties (Mojtahedi et al., 2015).

Sensorimotor memories are built from previous manipulations with an object or a similar object. When learning to manipulate an unfamiliar object, mismatches between the expected force and the actual force needed to manipulate an object can occur. In these instances, sensory feedback (visual, proprioception, touch) allows the digits to rapidly adapt to create the necessary amount of force to manipulate the object successfully (Ingram et al., 2011). The feedback is then used to update internal models of the object that can be used to form sensorimotor memories (Flanagan et al., 2006). Sensorimotor memories can then be used to anticipate the amount of force needed to successfully manipulate that object the next time (Fu et al., 2010; Mojtahedi et al., 2015).

Visual feedback provides information about an object's properties, such as size, texture, and density. By knowing these properties, predictions can be made about the amount of force necessary to manipulate an object with those properties. For example, if you were to pick up a big box you could predict that you would have to generate more force than if you were to pick up a smaller box. However, visual feedback does not always provide congruent information about an object's properties. In instances where visual feedback is incongruent, subjects would: first, generate incorrect forces based on incongruent visual information; then, learn to anticipate the

correct forces after multiple object manipulations and formation of sensorimotor memories (Fu & Santello, 2014). For example, if you were to pick up a small box you would expect to generate a small amount of force. But if the small box was filled with heavy rocks you couldn't see, then the small amount of force you generated would not be enough to lift the box. However, the next time you attempted to lift the box you would know from sensorimotor memory to generate a larger force to lift it successfully.

It is understood that visual feedback and sensorimotor memories support anticipatory force control. However, the extent to which visual feedback aids in anticipatory force control when information from feedback is incongruent with a key property of the object is unknown. In circumstances where visual feedback is incongruent, it has been assumed that subjects predominantly anticipate forces through learned experience with the object (i.e., sensorimotor memory). However, it is possible that visual feedback is still playing a role in anticipatory force control in these instances. It has been suggested that visual feedback can be used to identify and recognize objects so that the brain can retrieve sensorimotor memories (Johnsson & Cole, 1992). If visual feedback is useful when it is mismatched with actual object properties, it is unclear at what point (i.e., before reach or at grasp) visual feedback is helpful for anticipatory force control. Generally, whether the timing of this visual information matters in dexterous manipulation is less known. That said, the availability of visual feedback before and during reaching toward a target has been shown to be helpful for target localization, in addition to predictions about object properties (Desmurget et al., 1998). At grasp contact, visual feedback might be useful for anticipating forces based on where the digits land on the object surface since variability of digit position requires force modulation (Fu et al., 2010). To support the latter claim, visual feedback can influence force generation during grasp until approximately 100 ms

before lifting an object (Bozzacchi et al., 2018). Thus, it is possible that visual information at different timepoints provide the central nervous system with independent yet relevant components for the dexterous manipulation of an object.

The present study investigates the timed role of visual feedback for anticipatory force control when object properties are not salient. To examine this, the availability of visual feedback of the hand and object was manipulated before reach onset and after grasp to determine when it contributes to manipulating objects with non-salient properties, if at all. Based on previous work, it was hypothesized that when visual feedback is incongruent with a key property of an object, the availability of visual feedback before reach or at grasp will help access the sensorimotor memories needed to anticipate the forces required to successfully manipulate the object.

Methods

Participants

Sixty healthy subjects participated in this study (14 men, 34 women; age range: 18-44; median age: 21). Participants were right-handed with normal or corrected to normal vision. We excluded twelve participants as a result of equipment malfunction ($n = 7$) or subjects not completing the task properly ($n = 5$). Prior to participation, subjects gave written informed consent and were compensated \$15 per hour. All experimental procedures were approved by the Institutional Review Board at the University of Oregon.

Experimental Design & Procedure

To determine the contribution of visual feedback for manipulating objects with non-salient properties, we manipulated its availability before reach onset, after grasp, or both. This experiment used a between-subjects design which consisted of four visual feedback conditions with twelve participants assigned to each condition. The four conditions were visual feedback before reach onset and after grasp (onOn), visual feedback before reach onset only (onOff), visual feedback at grasp only (offOn), or no visual feedback at all (offOff).

In this experiment, a T-shaped object with a hidden asymmetrical mass distribution was used (Figure 1). To successfully minimize roll of the object, subjects had to generate a compensatory torque force (Nmm) opposite but equal to the torque force created by the asymmetric weight of the object. This task isolates planning from execution because relying on feedback of the object's properties after lift onset will result in the object tilting shortly after lifting. To successfully minimize tilt of the object, subjects needed to generate the correct amount of force at lift onset. If a participant could lift the object without ever letting it tilt, we

know that they planned the amount of force they were going to use before lifting the object. If the participant lifted the object and it initially tilted but adjusted so that it was level, it can be inferred that they used feedback after lift onset to generate the appropriate amount of force instead of planning ahead of time. From this, we can determine if participants were anticipating their force generation and determine the role of visual feedback.

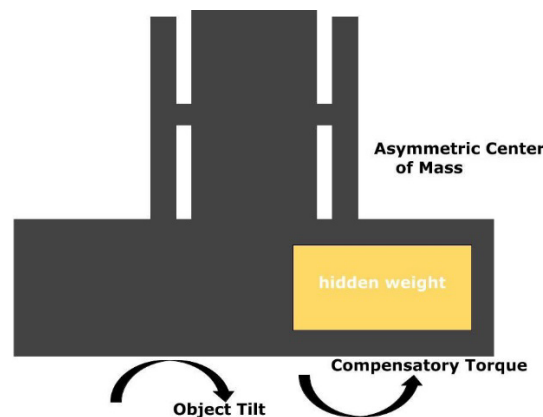


Figure 1. The symmetrically shaped object used in this experiment had a hidden weight that created an asymmetric center of mass that alternated between the right or left in blocked trials of 8. Subjects had to generate a torque anticipatorily at lift onset to prevent the object from tilting when lifted.

The object was 3D printed with carbon fiber containing nylon. The vertical column (height: 13.0 cm; width: 3.4 cm; depth: 5.0 cm) of the inverted T-shaped object was attached to elongated grasp surfaces on both sides (height: 7.0 cm; width: 3.2 cm; depth: 0.8 cm; between grasp distance: 8.5 cm). A lead block (height: 2.7 cm; width: 5.0 cm; depth: 3.0 cm; mass: 441 g) was concealed within the horizontal base on the left or right (trial dependent). The total mass of the object was 740 g with an external torque of 236 Nmm. At either side of the object, LED markers were placed on the outer tips of the aluminum rods to measure object torque. Force transducers, located in each grasp surface, measured grip and lift forces applied to the object by the digits. The position and roll of the object were measured using three radiofrequency-shielded

motion tracking cameras (Precision Point Tracking System, Wordvis). Using this system, the positions and object roll were recorded with near-infrared LEDs (frame rate: 150 Hz; camera resolution: 640 x 480 VGA).

Each trial began with the subject's right index finger placed on a button. An audio cue signaled them to release the button and reach for an inverted T-shaped object with a concealed asymmetrical mass distribution, which sat at arm's length on the table. A second audio cue signaled subjects to grasp the object with their thumb and index finger and lift the object while minimizing roll (Figure 2). Subjects had to compensate for the uneven weight of the object by applying more force to the heavier side to successfully maintain vertical alignment of the object. Participants were instructed to lift the object at a comfortable pace to an illuminated marker 10.5 centimeters above the table. Their goal was to reach, grasp, and lift the object without letting the object tilt.

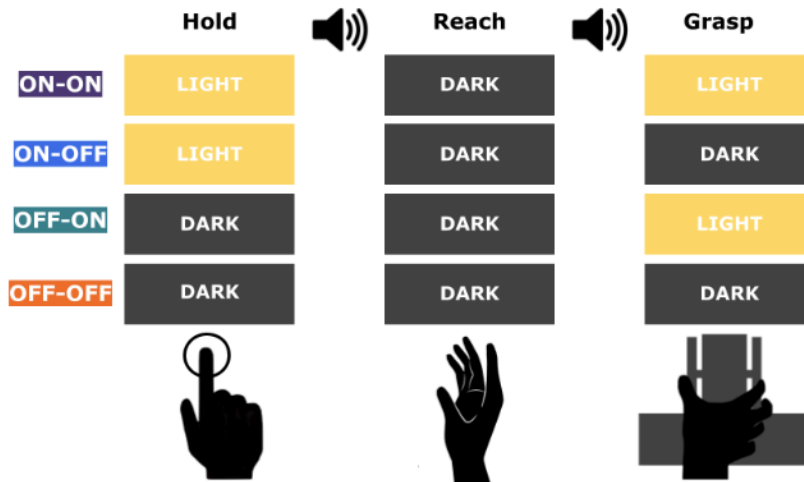


Figure 2. Participants completed the task in one of the four lighting conditions: onOn, onOff, offOn, or offOff. The conditions varied depending on when participants received visual feedback, if at all (onOn: visual feedback before reach onset and after grasp, onOff: visual feedback before reach onset only, offOn: visual feedback at grasp only, offOff: no visual feedback).

Before data collection, subjects completed practice trials to familiarize themselves with the task and practice reaching and grasping the object with the audio cues. The audio cues trained the participants to have a reach duration of one second. This ensured that participants all had equal reach phases so that potential differences between groups could not be attributed to the time spent in reach phase, but rather the differences in visual feedback before reach and/ or after grasp onset. The practice trials were done under the same lighting condition as their test trials. Additionally, during the practice trials, participants only grasped the object, and never lifted it to prevent learning. After each practice trial, they would receive verbal feedback that would let them know whether they needed to go slower, faster, or if their timing was good. Participants practiced until they completed four “good” trials in a row.

Once participants were finished practicing data collection began. The experiment consisted of four blocks of 16 trials each (64 total trials) with the object's center of mass (CoM)

alternating every eight trials (Figure 3). Participants were randomly assigned to have the hidden mass start on either the right or left side of the inverted T-shaped object.

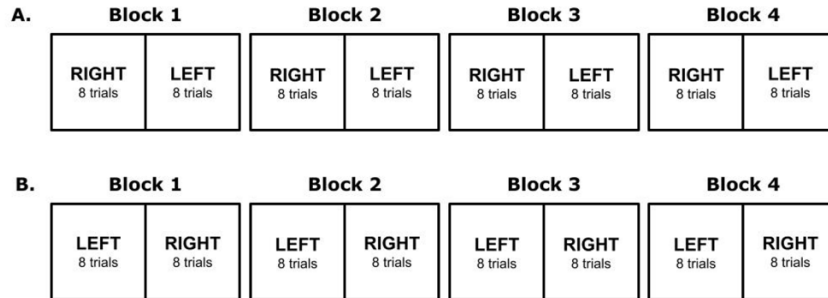


Figure 3. The experiment consisted of 4 blocks of 16 trials each (64 total trials). Each block had eight right center of mass trials and eight left center of mass trials with the order counterbalanced. Each participant started with either right or left for every block but were randomized between participants (A or B).

Data Analysis

Compensatory Torque

The net force generated by the index finger and thumb to keep the object from tilting due to its uneven mass distribution is known as the compensatory torque. This value can indicate whether participants were able to successfully minimize the tilt of the object or not.

Compensatory torque is generated by a combination of lift force (F_{tan}), grip force (F_n), and grasp configuration (GC) which is the vertical distance between the two grasping digits.

Compensatory torque can be represented by the following equation: (Marneweck & Grafton, 2020):

$$compensatory\ torque = \Delta F_{tan}(d_2) + F_n(\Delta GC)$$

The sign for compensatory torque (positive or negative) indicates the direction of the torque generated (positive for a clockwise torque and negative for a counterclockwise torque). In right CoM trials the compensatory torque, if successful, should be counterclockwise (negative)

and in left CoM trials the compensatory torque should be clockwise (positive), and to the same magnitude of the external torque.

Grip Force-Lift Force Coupling

Grip force-lift force coupling is a standard measure of anticipatory force control (Flanagan & Tresilian, 1994; Grover et al., 2019). The first force generated when grasping an object is the grip force, followed by lift force. Grip force is the force exerted by the fingers on the object, while lift force is the force acting in the direction of motion (the force acting vertically when lifting an object). The two forces tend to rise and fall together as forces are adjusted during object manipulation. How closely these forces are initiated from each other indicates the extent to which force generation was anticipatory. When the initiation of grip force and lift force happen far apart from each other we can infer that the action was not anticipatory, because it took longer to generate the lift force after generating grip force. It is also possible that a longer time between grip force and lift force could be due to participants adjusting their lift force based on their grip. Whereas, when the grip force and lift force initiate very close together, it is likely that the forces were planned ahead of grip contact because they were able to initiate their grip force and immediately generate their lift force to lift the object. To have these forces occur so closely together and successfully manipulate the object you must plan the forces in anticipation, rather than in response (Flanagan & Tresilian, 1994).

For each trial, the time of grip force initiation and lift force initiation were recorded. The timestamp for grip force initiation was defined as the time point where mean grip force exceeds a 0.2 N threshold and increases for 20 samples. The timestamp for lift force initiation was defined as the time point where net lift force exceeds a 0.2 N threshold and increases for 20 samples.

$$\text{mean grip force} = \frac{(\text{grip force of thumb})(\text{grip force of index})}{2}$$

$$\text{net lift force} = (\text{lift force of thumb}) + (\text{lift force of index})$$

To determine how closely grip force and lift force were coupled we found the difference between the initiation of each force.

$$\text{lift force onset} - \text{grip force onset} = \text{coupling}$$

Statistical Analysis

To investigate the contribution of timed availability of visual feedback for anticipatory force control when manipulating an object without salient properties, two variables were analyzed: compensatory torque and grip force-lift force coupling.

I checked the effect of manipulating the timed availability of visual feedback on task success with absolute mean compensatory torque using a one-way ANOVA with repeated measures between each condition for each block (Block 1: trial 1-16, Block 2: trial 17-32, Block 3: trial 33-48, Block 4: 49-64).

I determined if timed availability of visual feedback influenced anticipatory force control with the coupling measure using a one-way ANOVA with repeated measures between each visual feedback condition for each block. (Block 1: trial 1-16, Block 2: trial 17-32, Block 3: trial 33-48, Block 4: 49-64).

Lastly, to check the effect of timed visual feedback availability on anticipatory force control when a non-salient object property is altered, I compared the coupling measure using a one-way ANOVA with repeated measures between each visual feedback condition for each blocks post-rotation trials (Block 1: 1 and 9, Block 2: 17 and 25, Block3: 33 and 41, Block 4: 49 and 57).

Results

Forty-eight participants, reached, grasped, and lifted a symmetrical inverted T-shaped object with an asymmetrical mass distribution. The goal of the task was to maintain vertical alignment of the object by exerting a compensatory torque equal and opposite to the torque created by the weighted side of the object. Subjects were separated into four different experimental conditions based on when they received visual feedback. The onOn group received visual feedback before reach onset and grasp, onOff before reach onset only, offOn and grasp only, and offOff at neither reach onset nor grasp.

Compensatory torque produced by the participants to prevent the object from tilting when lifted was compared between each visual feedback condition for each of the four blocks. There was no significant difference in torque between each of the four conditions in any of the blocks (Figure 4). These results indicate that each group successfully compensated for the torque of the object created by the asymmetrical mass distribution to maintain vertical alignment and timed availability of visual feedback had no effect on achieving the task goal.

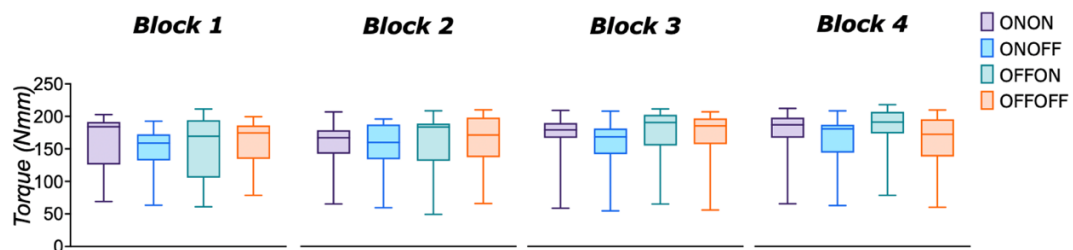


Figure 4. Box plots of the absolute compensatory torque generated at lift onset to prevent the object from tilting for each visual feedback condition and block. Bars represent the min and max torques.

Additionally, the temporal coupling between the initiation of grip and lift force was compared between each of the visual feedback conditions for each block. Block 1 showed no difference between visual feedback conditions; participants from each group were able to

generate their grip and lift force at a similar rate. By Block 4, the participants in the onOff and the offOn conditions showed a shorter temporal coupling between the initiation of grip force and lift force. (Figure 5). Therefore, subjects with visual feedback before reach onset and grasp contact (onOff and offOn) were able to generate the force required to minimize the tilt of the object more efficiently than the onOn and the offOff group in later blocks.

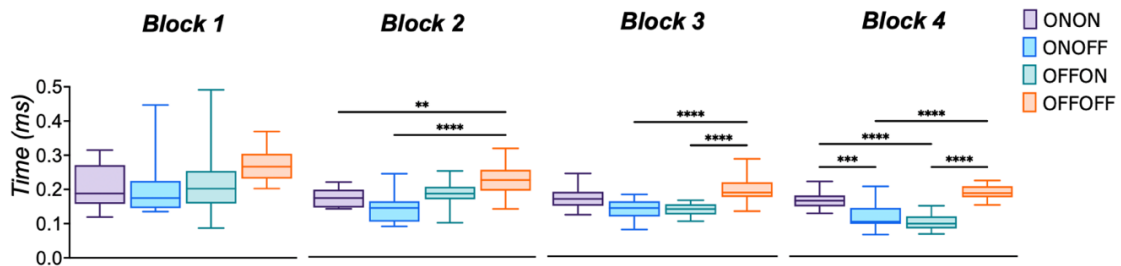


Figure 5. Box plots for the mean time between visual feedback conditions for each block. Time (ms) represents the coupling between grip force and lift force, meaning the time between the initiation of grip force and the initiation of lift force ($lf\ onset - gf\ onset = Time$). Bars represent the min and max time points. (* $p < 0.008$, ** $p < 0.001$, *** $p < 0.0001$, **** $p < 0.0001$)

The coupling of grip and lift force was also compared between each of the visual feedback conditions for post-rotation trials in each block. Post rotation trials were the first trials after the mass switched from either the right to left side or the left to the right side (Block 1: 1 and 9, Block 2: 17 and 25, Block3: 33 and 41, Block 4: 49 and 57). A post-rotation trial occurred every eight trials and required the participant to switch the direction they produce their compensatory torque. There was no difference in coupling found between visual feedback conditions for any of the blocks suggesting visual feedback is not useful when non-salient object properties are altered, at least during early sensorimotor learning (Figure 6).

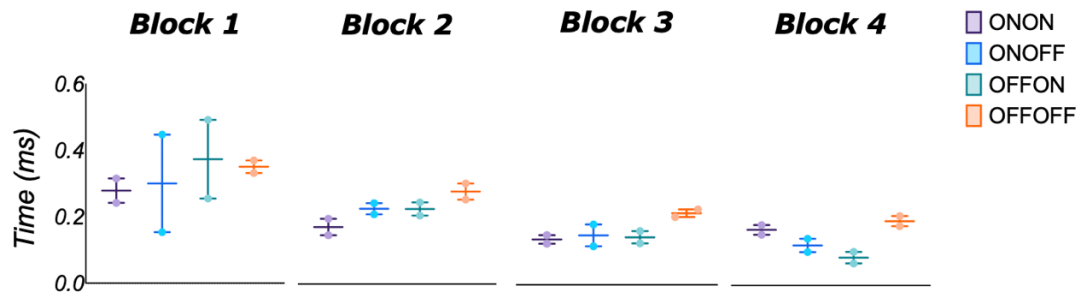


Figure 6. Box plots for the mean time of post-rotation trials in each block for each visual feedback condition (Block 1: 1 and 9, Block 2: 17 and 25, Block3: 33 and 41, Block 4: 49 and 57). Time (ms) represents the coupling between grip force and lift force, meaning the time between the initiation of grip force and the initiation of lift force ($lf\ onset - gf\ onset = Time$). Bars represent the min and max time points.

Discussion

In this study, it was hypothesized that when visual feedback is incongruent with a key property of an object, the availability of visual feedback before reach or at grasp will help access the sensorimotor memories needed to anticipate the forces required to successfully manipulate the object.

It was found that all groups across all blocks were able to compensate for the torque created by the uneven mass distribution of the object (Figure 4). In other words, the ability to generate the adequate amount of force to keep the object from tilting did not depend on when or if participants received visual feedback. This suggests that all participants acquired sensorimotor memory within 1-3 trials with or without visual feedback to help them achieve the task goal. This is consistent with previous research suggesting that participants can update internal models of an object and form sensorimotor memories after a few trials which allows them to manipulate objects successfully (Fu et al., 2010; Mojtahedi et al., 2015). It is also possible that because of the central nervous system's ability to adapt to whatever information it is given, participants can use a combination of previous experience (sensorimotor memory) and sensory feedback to generate force estimates and achieve task success (Körding et al., 2004).

Even though participants in all visual feedback conditions were able to successfully minimize tilt of the object, participants in the onOff and offOn conditions were more efficient in doing so, in later blocks (Figure 5). This resulted in swifter temporal coupling between the initiation of grip and lift force for participants in the onOff and offOn conditions. These results suggest that the availability of visual feedback before reach or at grasp improves the ability to access more established sensorimotor memories needed to anticipate the appropriate amount of force needed. It might also be that the participants in the onOff and offOn used visual feedback

differently based on when they received it. For instance, the availability of visual feedback before reach onset may be useful for accessing sensorimotor memory and target location (Desmurget et al., 1998), whereas having visual feedback at grasp may be helpful for making adjustments of anticipatory force based on where the digits land on the object, particularly when grasp surfaces are unconstrained (Johnsson & Cole, 1992 & Fu et al., 2010). These results also demonstrate that visual feedback is not required in advance (before reach) necessarily, and that the central nervous rapidly processes visual information after grasp for modulation of force control.

Surprisingly, the participants in the onOn condition, which had the most visual feedback, did not have as efficient of anticipatory force control as the other visual feedback conditions in later blocks (Figure 5). The onOn condition had visual feedback before reach onset, no visual feedback during reach, and visual feedback at grasp which gave them more switches in visual feedback availability than the other three conditions. A possible explanation for why subjects in the onOn condition were not as efficient is that they took more time between the generation of their lift force and grip force to evaluate whether their motor plan was still appropriate given the increased changes in available sensory information (Wessel & Aron, 2013).

Additionally, participants in the offOff condition, which had no visual feedback, were the slowest to generate the forces needed to successfully lift the object (Figure 5). This suggests that visual feedback is important for efficient retrieval of sensorimotor memories that can be used to manipulate objects with properties that are not salient. This finding is consistent with previous research showing that participants that are asked to manipulate novel objects are slower due to uncertainty about an unfamiliar object (Gordon et al., 1993). This can be applied to participants

in the offOff condition having the longest coupling time because of the uncertainty given by the lack of visual feedback.

Although participants with visual feedback were able to improve anticipatory force control overall, there was no difference in the coupling of the post-rotation trials in any of the visual feedback conditions (Figure 6.) The post-rotation trials were the trials that occurred following a switch in the mass distribution of the object, which occurred every eight trials (Block 1: 1 and 9, Block 2: 17 and 25, Block3: 33 and 41, Block 4: 49 and 57). When these switches occurred, participants would have to generate a compensatory torque opposite to what they had been using for the previous eight trials. Participants in all visual feedback conditions, across all blocks, were similarly inefficient at anticipatorily generating the forces required to lift the object suggesting that visual feedback is not helpful when object properties that are not salient are altered. During early sensorimotor learning, participants are likely relying on inflexible sensorimotor memories that are supplying information about the previous trials object properties, not the object properties of the current trial, therein resulting in task failure (Zhang et al., 2010).

A limitation that exists in this study is that there was no visual feedback in the reach phase of the experimental task. This meant that the onOn condition had to experience two switches of visual feedback availability (on before reach, off during reach, on during grasp), while onOff and offOn experienced one switch of visual feedback information (on before reach, off during reach and grasp; off before reach and during reach, on during grasp, respectively). Additionally, offOff didn't experience a switch in visual feedback availability at all. The additional switches in feedback may have impaired the participants in the onOn conditions performance which could have affected the interpretation of the data. In future studies, the experimental design should be altered so that all groups have equal switches in the availability of

visual feedback to determine the extent to which switching contributes to anticipatory force control.

The present findings demonstrate that visual feedback does play a role in anticipatory force control even when visual feedback is incongruent with a key property of an object. It was found that visual feedback is not necessarily required to successfully manipulate an object, but that having visual feedback before reach onset or at grasp improves efficiency of object manipulation, even when there is a mismatch between visual feedback and object properties. These findings demonstrate the importance of visual feedback for the retrieval of sensorimotor memories in motor tasks that involve anticipatory force control. The results from this study are applicable for future research in prosthetics. Visual feedback is important, but it is part of a complicated motor system, and its value and limitations are essential to understand when used to supplement systems with sensory deficits, such as prosthetics (Sensinger & Dosen, 2020). Visual feedback will allow for more efficient anticipatory force control to better manipulate objects with varying properties which would allow for greater functionality and independence for users of prosthetic limbs.

Conclusion

The goal of this study was to determine the role of timed availability of visual feedback for anticipatory force control when object properties were not salient. It was hypothesized that visual feedback would be useful even when it is mismatched with actual object properties. To determine this, the availability of visual feedback of the hand and object was manipulated before reach onset and after grasp to determine its contribution to manipulating an object with non-salient properties.

It was first determined that participants were able to successfully minimize the tilt of the object, irrespective of when or if they received visual feedback. However, participants that received visual feedback before reach or grasp were able to more efficiently generate the forces required to minimize object tilt in later blocks. These findings indicate that visual feedback is not necessary for task success, but improves efficiency of anticipatory force control, even when visual feedback is incongruent with the object's properties. This is explained by sensorimotor memories being formed regardless of whether visual feedback was available but are potentially more easily accessed by having visual feedback before reach or grasp.

In instances where unexpected events occur (e.g., switching of mass distribution) visual feedback is not useful. After switching the side of the mass hidden in the object participants were not able to efficiently generate the necessary amount of force needed to minimize tilt of the object. However, after a few trials of the mass being consistently on one side participants can update their sensorimotor memories to regain anticipatory force control, with participants who had visual feedback before reach onset or at grasp generating forces the most efficiently.

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