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A concurrent working memory task disrupts motor performance but preserves adaptation during dexterous object manipulation

Swarnab Dutta[1], and **Varadhan SKM**[2]

[1,2]Department of Applied Mechanics and Biomedical Engineering, Indian Institute of Technology Madras, Chennai, India

Corresponding author: Varadhan SKM (skm@iitm.ac.in)

Abstract

Dexterous everyday actions such as grasping and lifting objects rely on precise sensorimotor control and are often performed under concurrent cognitive demands. This study examined how cognitive load induced through a concurrent verbal working memory task affects sensorimotor integration in anticipatory adaptation during object manipulation. Participants adapted to an asymmetrical mass distribution by generating compensatory moments at object lift onset, with the aim of minimising object roll. Sensorimotor adaptation performance and grip force modulation were assessed under both single-task (motor only) and dual-task (motor plus working memory) conditions. Results showed that cognitive load led to longer reaction times and increased grip forces, indicating cognitive-motor interference consistent with previous literature. Crucially however, the trajectory of the adaptation to novel object dynamics remained robust even under the concurrent cognitive load. This resilience suggests that the core processes of error-driven, trial-by-trial motor adaptation, which hinge on salient, task-relevant visual and haptic feedback, may be relatively immune to concurrent working memory demands.

Keywords: *dual-task, working memory, anticipatory control, sensorimotor adaptation, cognitive-motor interference, object manipulation*

Introduction

The ubiquitous nature of everyday object interactions belies the complex processes in our brain that facilitate these actions. These processes rely critically on sensorimotor integration, which represents how appropriate motor actions, such as fingertip placement and force distribution, are generated by integrating sensory information about our body and the external environment (Wolpert et al., 1998; Ordás & Alonso-Frech, 2024). While seemingly automatic, these dexterous interactions actually require considerable cognitive resources to be executed successfully. In reality thus, cognition and action are richly intertwined and how we grasp objects often reflects multi-order planning (Rosenbaum et al., 2012). This competition for resources has a profound consequence on our daily living since we frequently find ourselves in object manipulation settings which simultaneously demand substantial cognitive effort, such as handling a cup of coffee while having a conversation. The dual-task paradigm has been a widely used experimental approach in this regard for investigating how different tasks draw on shared processing resources (Abernethy, 1988; Kahneman, 1973; Pashler, 1994). By comparing the performances between dual-task and single-task conditions, researchers can infer the degree of resource overlap. Altered motor and/or cognitive performance during cognitive-motor dual-task experiments, where a primary motor/cognitive action is paired with a secondary cognitive/motor task, is thought to indicate overlapping demand between the two tasks for the

limited attentional resources during their concurrent execution, leading to task prioritisation strategies where one task is maintained at the cost of the other. Two main theories have been attributed towards cognitive-motor interference during dual-task performance, the limited attentional capacity sharing and the bottleneck model [reviewed in (Leone et al., 2017)].

Research has demonstrated the interference of high level cognitive tasks with the performance of movements concerning the upper limb such as reaching and grasping (Li et al., 2009; B. Lee et al., 2014; Spiegel et al., 2013, 2014; Gunduz Can et al., 2017), precision and power grip squeezing (van Dijck et al., 2015), force tracking (Voelcker-Rehage et al., 2006; Au & Keir, 2007; Mehta & Agnew, 2011; Temprado et al., 2015), and tapping (Serrien, 2009; Fraser et al., 2010; Korotkevich et al., 2015). In the precision grip lift domain though, only a few studies have studied the interaction of cognitive loading and motor behaviour with emphasis on grip kinetics. Within these, two studies by Guillery et al. (2013, 2017) probed the temporal and dynamic parameters of the grip and lift forces under cognitive load. With a concurrent visual search and counting task, the preload phase was lengthened and both the maximum grip force and the grip force during the hold phase were elevated compared with the motor-only condition (Guillery et al., 2013). With a concurrent letter-string working memory task, the preload phase was again lengthened, and under high load the load phase was shortened and the lift phase lengthened. In this study, grip force was also elevated at lift-off, at its maximum and during the hold phase (Guillery et al., 2017). In sum, the literature suggests that even routine skilled object interactions are far from being entirely automatic and, instead, may involve or interact with higher cognitive functions during both planning and execution. Despite these advances, there remains a critical gap in our understanding of cognitive-motor object interactions with regard to sensorimotor adaptation, particularly since dexterous manipulation often requires adaptation to objects with varying physical properties. When encountering new or altered object dynamics, individuals typically engage in sensorimotor adaptation, a form of motor learning wherein the motor system adjusts to novel sensorimotor relationships through repeated interactions by remapping the sensory inflow and motor outflow, thus learning a new sensorimotor transformation.

There has been extensive research examining cognitive-motor interference in sensorimotor adaptation outside the domain of object manipulation. The mechanisms underlying this interference has been shown to operate at multiple levels of sensorimotor processing. (Redding et al., 1992) proposed while studying prism adaptation that adaptive coordination arises through flexible linkages between sensorimotor subsystems such as eye–head and hand–head coordination, while spatial realignment depends on adaptive encoding mechanisms within these interconnected subsystems. When coordination relies mainly on automatic processes, these linkages can remain sufficiently engaged under cognitive load to enable meaningful realignment, though overall performance and coordination may be suboptimal. (Ingram et al., 2000) later investigated the role of proprioception in adaptation to visuomotor perturbations, showing that while proprioceptive input is not absolutely essential for adaptation in reaching movements, its role in the control of visuomotor adjustments is more nuanced, in that attention becomes necessary to monitor movements when proprioceptive feedback is unavailable. At the feedback control level, divided attention did not impair within-movement feedback adjustments of the arm but substantially reduced subsequent movement adaptation by

disrupting error encoding and the transformation of errors into predictive corrections. Also, the difficulty of secondary categorisation tasks differentially taxed executive resources, leading to a proportional decline in adaptation performance (Taylor & Thoroughman, 2007, 2008). More recently, it has been shown that task context also matters, and in this regard, the consistency of attentional resource availability from motor memory formation to recall modulates the stability of visuomotor learning (Song & Bédard, 2015). Furthermore, these effects are not uniform across the lifespan. For instance, dual-tasking during split-belt treadmill adaptation in older adults results in slower and more variable temporal adaptation and larger variability during de-adaptation, underscoring the importance of accounting for cognitive–motor interference in rehabilitation design (Conradsson et al., 2019). Age-dependent differences also appear during dual-task locomotor adaptation wherein young adults maintain cognitive performance with mild decrements in motor adaptation, whereas late middle-aged adults prioritise motor adaptation at the expense of cognitive performance, with no age related differences in savings across dual-task conditions (Rossi et al., 2021). However, the secondary tasks used across these studies varied considerably in cognitive demand, making it difficult to determine how the burden of the secondary task quantitatively relates to motor performance.

In object manipulation, one paradigm through which sensorimotor adaptation has been investigated is by systematically varying the mass distribution (centre of mass) of the object to be interacted with. Successful adaptation to objects with such asymmetrically loaded objects necessitates the anticipatory production of a compensatory moment at lift onset to counteract the eccentricity, akin to how we might prevent spilling while interacting with a cup of hot tea. Object lift onset is that instant when sensory information about the object dynamics becomes completely available to the participant and marks the end of predictive control. The importance of predictive control mechanisms in our regular actions and interactions cannot be emphasised enough. If we depended solely on feedback-based control, our movements would show delays, thus compromising their characteristic fluidity and accuracy. The anticipation relies on internal representations of the object dynamics developed from long-term associations as well as *sensorimotor memories*, i.e., stored associations between previous hand-object experiences and the object properties (Johansson & Westling, 1988; Gordon et al., 1993; Albert et al., 2009; Marneweck et al., 2018; Schneider et al., 2019; Dutta & Skm, 2024). Traditionally, this framework employed *constrained* grasping wherein the contact points would be pre-selected because of the limitations associated with fixing the force sensors at one position on the object (Albert et al., 2009; Salimi et al., 2000). This context of grasping demonstrated predictive force control that was dependent only on the *sensorimotor memory* of the force distribution. More recently, this has been extended to *unconstrained* grasping which has allowed for the choice of contact points, thereby lending greater ecological relevance since our real-world interactions rarely use predetermined grasp points. This new paradigm suggested the formation of high-level internal representations of the object dynamics that were robust to variabilities in the contact points. The necessary anticipatory commands were thought to be enabled by the internal representation of the object's dynamics, which is continuously integrated and updated from one trial to the next using feedback about the contact location on the object (Fu et al., 2010; Fu & Santello, 2014; Parikh et al., 2020). The learning of such sensorimotor transformations occurs rapidly within a few trials through multisensory

integration. Two principal modalities inform this process, firstly, the visual feedback guided peak roll, which occurs just after the object lift onset. Once the compensatory moment is learnt, i.e., a stable internal representation is formed and appropriately applied to the eccentrically loaded object, peak roll also minimises. And secondly, tactile and proprioceptive inputs relaying information about the object dynamics after the object is lifted. Tactile feedback signals are used to monitor task execution by comparing real-time sensory inputs to expected signals at distinct sensorimotor control points, i.e., initial object contact or onset of object lift (Birznieks et al., 2001; Johansson & Birznieks, 2004; Johansson & Flanagan, 2009). And consequently, any mismatch elicits corrective actions to adjust the motor plan.

In relation to the aforementioned anticipatory adaptation to asymmetrically loaded objects, dual-tasking with cognitive load may compromise both the sensory aspects of such adaptation. Studies have shown that cognitive load affects the ability to detect changes in the visual environment as well as influences oculomotor behaviour in the visual processing of natural scenes (Y.-C. Lee et al., 2007; Walter & Bex, 2021). Thus, attentional resources allocated towards a concurrent cognitive task in the dual-task setup may attenuate visual feedback, potentially reducing the saliency of the critical error signal (peak object roll) driving the trial-to-trial learning. Furthermore, research has also demonstrated the impact of cognitive load on the processing of spatio-temporal properties of haptic signals (Haghighi et al., 2020). So, processing of the haptic feedback that signal actual object dynamics may also be degraded under cognitive load, further hampering the extraction of relevant information for adaptation. We thus hypothesised that the sensorimotor adaptation trajectory will be altered under additional cognitive load in a dual-task setting due to interference with multisensory integration. Moreover, we also tested if this interference was differentially sensitive to whether the choice of contact points was allowed or not. Our expectation was that unconstrained grasping (free choice of contact points) would increase cognitive demand compared to constrained grasping (cued contact points), because participants must simultaneously plan both the motor action and the grasp configuration.

Methods and Materials

Participants

A total of 44 participants (22 females and 22 males; mean age: 24.6 ± 3.6 years), all right-hand dominant as assessed by the Edinburgh Oldfield Handedness Inventory (Oldfield, 1971), with normal or corrected-to-normal vision, were included in the study. None of the participants reported any history of neurological or musculoskeletal disorders affecting the involved upper limb, were naive to the study's purpose, and provided written informed consent. The protocol was approved by the IIT Madras Institutional Ethics Committee (IEC/2023-01/SKM/20), with sessions conducted per the approved procedures, and participants received financial compensation per institute norms for a ~1-hour session.

Experimental apparatus

Two six-axis force and moment transducers (Nano 17, Force resolution: 0.0125 N in tangential and normal directions; ATI Industrial Automation, Garner, NC, USA) were instrumented onto an inverted T-shaped acrylic manipulandum to measure the forces and moments produced by the index finger and thumb (see **Fig. 1**). The manipulandum used in this study, albeit with modifications, was also employed in our previous work which addressed a different research question (Dutta & Skm, 2024). Grasp surfaces were made of polycarbonate panels covered with P320-grit sandpaper (3M) and were mounted on each sensor vertically. The apparatus recorded *grip* and *load* forces (normal and tangential to the contact surfaces, respectively) and the *centre of pressure* (COP) of each digit. The graspable panels included a longitudinal flange to prevent bending from the normal forces. At the base of the manipulandum, an acrylic box with three compartments (one at the centre and one on each side) allowed the addition of external weights to alter the mass distribution while the manipulandum itself weighed 465 g without any external weight. The inverted T-shaped manipulandum had an overall height of approximately 200 mm and a grasp aperture (distance between thumb and index finger contact surfaces) of 63 mm. The polycarbonate grasp surfaces were 22 mm wide and 140 mm tall, mounted vertically on each sensor on the central vertical post. The slotted box underneath was 186 mm wide, 45 mm deep, and 54 mm in height. Object lift onset was identified as the moment when any of the two lift switches placed under the base of the apparatus on the table was released by upward movement. An inertial measurement unit (IMU; BNO055, Bosch, 16-bit resolution, 2000°/s range) was mounted on the bottom of the manipulandum. As the manipulandum is a shared laboratory apparatus, the IMU had already been installed for our previous study (Dutta & Skm, 2024), and in the present study it was kept attached and recorded only as a backup. Its vertical acceleration signal could be used to identify lift onset if one of the lift switches failed to trigger, and it could also help resolve trials with ambiguous force/torque data. As the lift switch and force/torque signals were clean for all participants, this backup was not needed, and the IMU data were not analysed. The exact locations of the sensors on the grasp surfaces were obscured from participants using a cover plate to prevent the influence of visual cues during fingertip placement. Two arrays of four red LEDs (approximately 5 mm each, array width ~22 mm), installed along the cover plate's inner edges collinearly, served as finger placement cues when illuminated, and the plate's lengthwise perforations (hole diameter ~ 0.8 mm) allowed only the light to be seen, thus preventing spatial cues about the LEDs location when turned off. The LED cue arrays were positioned at collinear locations on the grasp surfaces, vertically centred with the array centre at 70 mm height from the bottom/top of each grasp surface. In the constrained grasp context, these positions remained fixed throughout all trials. A concealed 400 g mass was added in each lift, to the right compartment at the base from the point of view of the participant, yielding an external moment of 255 N-mm in the frontal plane and bringing the total manipulandum weight to 865 g. The placement of the additional weight was hidden to prevent anticipation of mass distribution.

Experimental design

The entire experiment was split into four groups viz. **Dual task Unconstrained (DTU), Dual task Constrained (DTC), Single task Unconstrained (STU), Single task Constrained (STC)**. All the participants were randomly allocated to one of these four groups. Everyone performed the experiment with their dominant (right) hand. There were twenty trials or object

lifts per participant throughout the experiment. The design did not include a separate baseline or post-adaptation phase. Apart from three familiarisation trials with the external weight in the centre compartment, participants were exposed to the asymmetric mass distribution from the first trial, so that the full adaptation trajectory could be captured. A baseline block would have lengthened the session and increased the risk of fatigue in the dual-task protocol, and retention and after-effects were outside the scope of the study. Midway through the experiment, participants had the chance to rest for a minimum of five minutes to minimise overexertion induced interference in task performance and motor behaviour.

In the dual-task conditions DTU and DTC, the participants performed a motor task simultaneously with a cognitive task that loaded the working memory. For this we adapted the string recall task used in (Guillery et al., 2017) with targeted modifications. The participants were asked to perform the cognitive task as accurately as possible, beside which there were no other explicit directions indicating any priority to the motor or the cognitive component of the task.

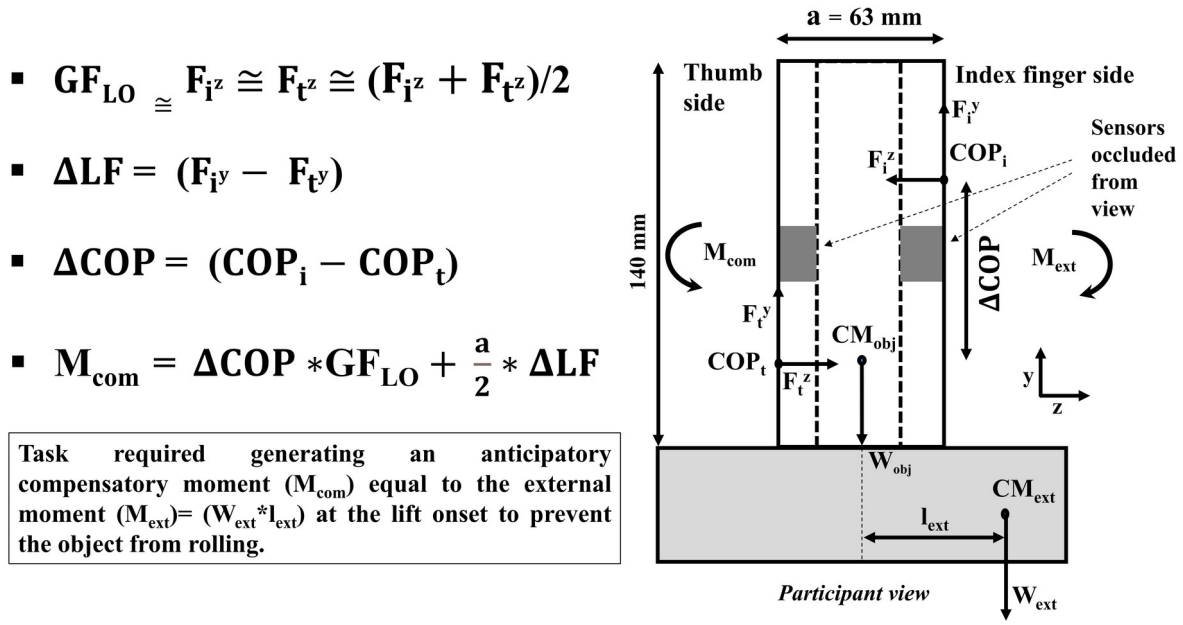


Fig. 1. Experimental setup. Participants grasped an inverted T-shaped manipulandum while exerting fingertip forces in the normal z-direction (grip, F_z) and tangential y-direction (load, F_y); the free body diagram of the manipulandum shows each fingertip's centre of pressure (COP), grasp aperture (a), the object's centre of mass (CM_{obj}) and its weight W_{obj} excluding the added mass, the external weight (W_{ext}), and the external weight's centre of mass (CM_{ext}). A compensatory moment M_{com} was required to counter the external moment M_{ext} = 255 N·mm caused by a 400 g mass placed in the rightmost slot at a distance l_{ext} = 65 mm from the object's centre. Static equilibrium analyses were limited to the frontal (YZ) plane.

In the single-task conditions STU and STC, the participants performed the same motor task without any concurrent cognitive task. In all four conditions, the motor task involved reaching, gripping, and lifting. As instructed, participants were required to reach for a manipulandum, grasp it with the thumb and index finger fingertips on the grasp surfaces, and lift it to a comfortable height of approximately 12 cm, indicated by a height marker placed beside the object. Participants were also instructed to lift the object straight up to minimise horizontal movement. Lift height and horizontal movement were not measured, but the experimenter visually monitored lift height on every trial for compliance. They were to perform this movement naturally and without hesitation, while trying to minimise any tilting of the object as much as possible. For the *unconstrained grasp* groups DTU and STU, participants were directed to position their fingertips on the grasp surfaces with self-selected contact points while avoiding the edges. For the *constrained grasp* groups DTC and STC, the participants were directed to lift the object by grasping at the visually cued contact points. The positions on the graspable panels that provided visual cues for the grasp points remained consistent throughout the experiment.

At the start of the experiment, all the participants were instructed to wash and clean their hands with soap, dry them with a towel, and then sit comfortably on a wooden chair. They were directed to keep their performing hand on the table with the palm resting on a platform instrumented with two lift switches, designed to capture the movement onset. Participants were seated comfortably with the manipulandum positioned ~30 cm in front of their body. The manipulandum base rested on the table atop a 5 cm height platform, positioning the object at a comfortable height. The manipulandum was placed along the parasagittal plane passing through the right shoulder, ensuring ergonomic reach with minimal shoulder abduction. Under the dual-task conditions, each trial began with the presentation of a pseudo randomly chosen sequence of letters on the screen in red colour against a grey background. These letters were drawn from the following pool: J, K, L, M, N, P, Q, R, S, T, and V. The number of letters in each sequence was tailored to each participant, based on their individual letter memory span determined prior to the experiment. This pre-experimental assessment is described in detail in the following section. Once assessed, this sequence length remained constant throughout the entire experimental session. To prevent the use of mnemonic strategies like splitting the letters into pronounceable chunks or pseudo-words, vowels were excluded from the sequences and so were familiar acronyms. The sequence was displayed for 2.25 s, following which the sequence disappeared, and an auditory cue was heard prompting the participants to start reaching for the object to lift it. The participants were instructed at the beginning of the experiment to direct their gaze at the manipulandum once the sequence disappeared. Then, after 7 s, the second auditory tone occurred, signalling the participant to replace the manipulandum on the table. Finally, after the replacement was complete, a single letter belonging to the initially presented sequence was displayed for 1 s, and the participants were asked to verbally report which letter followed the presented letter according to the sequence shown at the beginning of the trial. Participants were instructed to perform the reach–grip–lift task naturally. The motor task duration was standardised at 7 seconds (from first auditory cue to second auditory cue) to provide sufficient time for reach, grasp, lift (~12 cm height), and replacement. Under the single task conditions, a red fixation cross on the screen substituted the sequence presentation in the

scheme of the trial **(Fig. 2)**. In both conditions, there was a 0.5-second delay between letter sequence/fixation cross disappearance and the first auditory cue, allowing participants to shift gaze from screen to manipulandum. There was no fixed inter-trial interval and trials proceeded continuously after object replacement and cognitive task response. To familiarise with placing their fingertips on the cues and the protocol in general, the participants in each of the four groups performed three practice trials with the external weight in the centre compartment at the onset of the experiment. A successful motor performance required participants to anticipatorily generate a compensatory moment (M_{com}) equal in magnitude but opposite in direction to the external moment (M_{ext} = 255 N·mm) at lift onset to minimise object roll. In this sense, successful adaptation is operationalised in the present study as a trial-by-trial increase in compensatory moment towards $M_{ext.}$ We used M_{com} as the measure of anticipatory control and did not analyse peak roll because M_{com} is generated before lift onset and directly reflects the predicted object dynamics, whereas peak roll, which occurs after lift onset, is the consequence of this anticipatory torque. Furthermore, M_{com} at lift onset is strongly correlated with peak object roll (Fu et al., 2010; Parikh et al., 2020) and it has been used on its own to index anticipatory control of object tilt (Davare et al., 2019; Parikh et al., 2020; Schneider & Hermsdorfer, 2021).

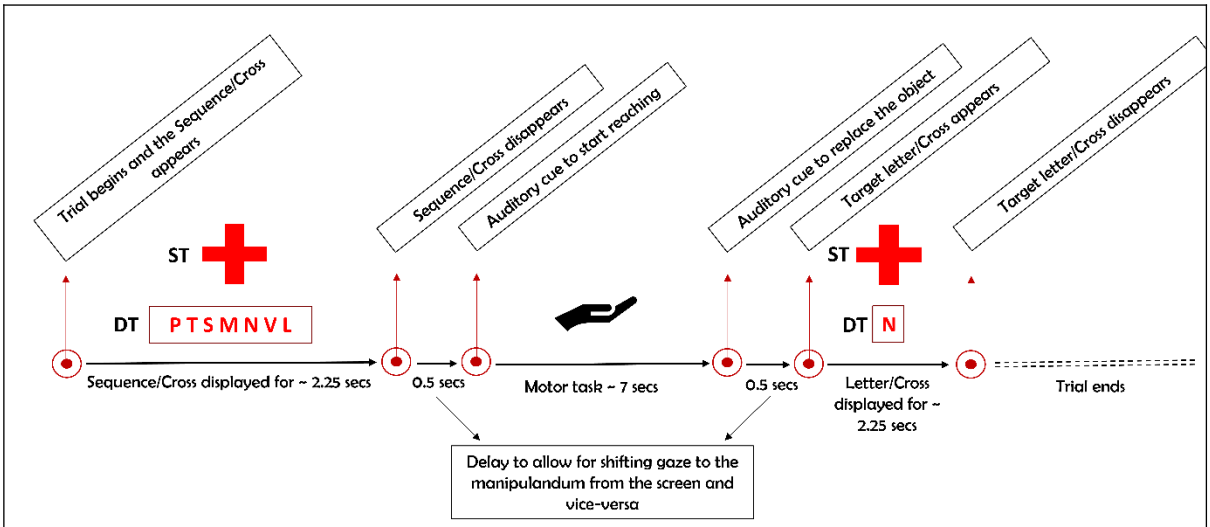


Fig. 2. Schematic of the experimental protocol for both dual task and single task conditions. In the single task (ST) condition a red fixation cross replaced the randomised string and the target letter presented during the dual task (DT) condition. All participants were randomly assigned to one of the four groups: *Dual task Unconstrained (DTU)*, *Dual task Constrained (DTC)*, *Single task Unconstrained (STU)*, and *Single task Constrained (STC)*. For the c*onstrained* grasp context, i.e., for STC and DTC, contact cues were presented on the object whereas for the *unconstrained* grasp context, i.e., for STU and DTU, participants were allowed the choice of finger placement on the object.

Coefficient of friction measurement

Since the grip force needed to hold an object securely without it slipping from the fingers, is a function of the friction between skin and the object's grasp surface, we measured the coefficient of static friction (μ) between the skin and the sandpaper before the experiment. We employed the imposed displacement method (Savescu et al., 2008) through a timing belt-pulley system powered by a servomotor for this measurement. For more details, refer to (Rajakumar & Skm, 2020). Briefly, a six-component force/torque sensor (Nano 25; ATI Industrial Automation, Garner, NC) mounted on a custom aluminium platform driven by a servomotor via timing belt-pulley mechanism recorded normal and tangential forces. Participants pressed downward with index finger or thumb separately to maintain 6 N normal force for 3 s (visual feedback on monitor), with the forearm/wrist immobilised using Velcro straps and palm supported by wooden block. The platform then translated away at 6 mm/s until slip onset. Coefficient of friction was calculated as tangential force divided by normal force at the precise moment of slip initiation, providing a finger-specific friction estimate under standardised conditions. Data were acquired via custom LabVIEW software.

Pre experimental evaluation

To ensure that the cognitive component in the dual-task conditions was tailored to each participant's abilities and to avoid presenting sequences that exceeded their memory capacity, each individual's working memory capacity was evaluated by measuring their memory span for letters, following a method similar to the digit span subtest of the Wechsler Memory Scale (Wechsler, 1981) in line with (Guillery et al., 2017). In this method, participants were shown a string of consonant letters on a screen for 2.25 seconds. Immediately after the letters disappeared, they were asked to recall and repeat the entire sequence in the correct order. The assessment began with three-letter sequences, and after every two consecutive correct recalls, an additional letter was added. The process continued until a participant failed to correctly repeat a sequence, at which point the assessment stopped. The longest sequence successfully recalled determined the individual's memory span. In addition to the memory span assessment, before the experiment, cognitive function of all participants was tested using the Mini-Mental State Examination [MMSE;(Folstein et al., 1975)] screening.

Data acquisition

The data from the force/torque (F/T) sensors, the IMU, and signals from the lift switches capturing both movement and lift onsets were recorded using custom LabVIEW software at a 200 Hz sampling rate. The F/T data were digitised via a NI DAQ 16-bit A/D board (USB 6225, National Instruments, Austin, TX, USA) and processed using a second-order zero phase lag Butterworth low-pass filter with a 15 Hz cutoff frequency. IMU data collected from the object were digitised through a Teensy 4.0 microcontroller and synchronised with the F/T data. Additionally, a NI DAQ 16-bit A/D board (USB 6002, National Instruments, Austin, TX, USA) was employed to acquire the lift switches' signals and to supply power to the LED arrays.

Data analyses

All data were processed offline using MATLAB (Version R2022a, MathWorks, USA). The analyses focused on several key epochs, as outlined below:

Loading phase was defined as the period between the digits' early contact with the object and the object lift onset.

Early contact was defined as the moment when the sum of thumb and index finger's normal forces exceeded a threshold of 0.1 N and remained above it for the subsequent 200 ms.

Object lift onset was defined as the moment when either of the two object lift switches were released and stayed open for the next 50 ms. This is the decisive moment when the participant gains complete sensory information about the object's dynamics.

Movement onset indicating the reaction time was defined as the instant when both the palm platform lift switches were released and remained open for the following 100 ms.

Hold phase was defined as the duration during which the object is held steadily after being lifted.

Safety margin (SM) refers to the additional normal force applied beyond the minimum necessary to prevent the handheld object from slipping. We computed instantaneous *SM(t)* for both the index finger and thumb using the following equation **(Eq. 1)** (where μ is the participant coefficient of friction between the finger and sandpaper computed from the friction experiment data, t refers to the time course of the hold phase, F_t is the vertical tangential force, F_n is the normal/grip force).

$$SM(t) = \frac{\left[\, F_n - \frac{|F_t|}{\mu} \,\right]}{F_n} \qquad \textit{Eq. 1}$$

Due to the eccentric load, the required load force is greater for the index finger than for the thumb by design, whereas the grip forces applied by both digits remain similar. To obtain an unbiased measure, we therefore averaged the SM values of the index finger and thumb. This averaged SM was then subjected to a Fisher's Z-transformation **(Eq. 2)** and used for statistical analyses.

$$SM_z = 0.5 * \ln\left(\frac{1 + SM}{1 - SM}\right) \qquad \textit{Eq. 2}$$

The *centre of pressure*, which is the location where the resultant fingertip forces act on the grasp surfaces, was determined using the force and moment components measured by the respective F/T sensors in their reference frames, according to the following formula. **(Eq. 3)**

$$COP_y = \frac{\left(M_x - F_y * d\right)}{F_z} \qquad \textit{Eq. 3}$$

(COP_y = Centre of pressure of a digit along the Y-direction, M_x = Moment in the X-direction, F_y = Force in the Y-direction, F_z = Force in the Z-direction, d = Thickness of the graspable panels; 9 mm)

The fingertip forces and centres of pressure from each F/T sensor were used to calculate the following performance variables that underlie the compensatory moment:

a. The average fingertip grip force at object lift onset ($\mathbf{GF_{LO}}$). The grip forces on each side are assumed to be approximately equal, i.e., $\mathbf{F_z^i \approx F_z^t \approx GF_{LO}}$**,**
b. The difference between the load forces applied on the index finger side and the thumb side of the object (**ΔLF**), and
c. The vertical gap between the centres of pressure (COP) on the manipulandum's index finger and thumb sides, (**ΔCOP**).

The compensatory moment computed at the object lift onset (M_{com}) in the frontal (YZ) plane is recognised in motor control literature as a reliable indicator of predictive processes, as it reflects predictive force control occurring before complete sensory feedback about the object's weight and weight distribution is obtained (Salimi et al., 2003; Fu et al., 2010). This compensatory moment, which serves to minimise the peak object roll, can be expressed as a simplified function of the variables mentioned earlier using the following static equilibrium equation (Eq. 4), in relation to balancing the manipulandum's eccentricity caused by the external mass**.**

$$\mathbf{M_{com}} = \Delta LF * \frac{a}{2} \blacklozenge \Delta COP * GF_{\mathbf{LO}} \qquad \textbf{\textit{Eq. 4}}$$

All the performance variables mentioned above were computed at the object lift onset. As previously stated, the individual components in the expression for the compensatory moment can be divided into the sum of two moments, namely

1. **ΔLF * a/2:** The moment generated by the product of the difference between the tangential forces of the index finger and thumb and half of the grasp aperture (a = 63 mm).
2. $\mathbf{GF_{LO}}$ *** ΔCOP**: The moment generated by the product of the average grip force of the index and thumb and the difference between the index and thumb centres of pressure on the grasp surfaces.

The exerted moments on the manipulandum were considered positive when they acted opposite to the external moment. Therefore, from the participant's perspective, moments applied in the anti-clockwise direction while using the right hand were regarded as positive moments and vice-versa.

Statistical analyses

All statistical analyses were performed in the R environment for statistical computing (R Core Team, 2021). Two-way ANOVAs were conducted using `stats::aov()` with `car::leveneTest()` for homogeneity of variance on the *motor performance variables*, namely, $\mathbf{GF_{LO}}$, i.e., the average fingertip grip force at object lift onset., $\mathbf{GF_{max}}$, i.e., the maximum of the average grip force during the trial**,** $\mathbf{GF_{hold}}$**,** i.e., the average of the average grip force during the hold phase, $\mathbf{SM_{avg}}$, i.e., the average safety margin, and the *chronometric measures*, namely, **Reaction time (RT),** i.e., the time elapsed before movement onset**, Loading phase duration (LPD), i.e.,** the

duration of the loading phase**,** and **Reach duration (RD), i.e.,** the time taken from movement onset to early contact with the object, with **context (levels: *con, uncon*)** and **condition (levels: *DT, ST*)** as between-subject factors. Effect sizes were computed using `effectsize::eta_squared (partial = TRUE)`. To analyse the modulation of the compensatory moment at lift onset (M_{com}) across trials, a linear mixed-effects model (LMM) with polynomial predictors was fit using the lme4 package (Bates et al., 2015) using `lme4::lmer()`. Linear mixed models (LMMs) extend traditional regression by estimating fixed effects (predictors at the group level) alongside random effects, which capture the variability of these predictors across randomly selected individuals. This method accommodates nested data structures and helps prevent anticonservative inference (Pinheiro & Bates, 2000; Aarts et al., 2014). The model included the categorical predictors; *condition* and *context*, continuous predictors *trial* and *trial²* to capture linear and quadratic trends, as well as random intercepts for subjects and random slopes for trial. Due to convergence issues, random slopes for trial² were omitted. The initial model specification was:

$$\mathbf{M_{com} \sim context * condition * trial * trial^2 + (1 + trial \mid subject)}$$

Model selection based on Bayesian Information Criterion (BIC), favoured a reduced model without context and related interactions (lower BIC). This indicated that inclusion of context did not markedly improve model fit. Therefore, the final model chosen was:

$$\mathbf{M_{com} \sim condition + trial + trial^2 + condition: trial + condition: trial^2 + (1 + trial \mid subject)}$$

The second-order polynomial (trial + trial²) was used as a descriptive approximation of the compensatory moment trajectory across the 20 trials, which showed a steep rise followed by a slower increase. This model was chosen because its linear and quadratic terms allow two features of the trajectory, the rate of increase and its slowing over trials, to be compared separately between conditions. Double-exponential mixed models did not converge reliably with 20 trials per participant, and a log(trial) model describes the trajectory with a single parameter, allowing only a coarser comparison. As a robustness check, the log(trial) model was nevertheless fitted (see Results). P values for fixed effects in the LMM were obtained by Wald-type t-tests using Satterthwaite's method to approximate degrees of freedom, as implemented in the lmerTest package (Kuznetsova et al., 2017). To quantify variance explained by the models, marginal R^2 (variance explained by fixed effects alone) and conditional R^2 (variance explained by both fixed and random effects) were computed using the piecewiseSEM package (Lefcheck, 2016) according to established procedures (Nakagawa & Schielzeth, 2013) through 'piecewise::rsquared()'. Marginal R^2 values are analogous to classical R^2, but specifically reflect the proportion of variance accounted for by fixed predictors. Statistical equivalence testing of the linear and quadratic trends between conditions was conducted using two one-sided t-tests [TOST; (Lakens, 2017)]. Estimated marginal trends (i.e., slopes for trial and curvature for trial²) were extracted for each condition using the emtrends function from the emmeans package (Lenth, 2025). Inference for these trend contrasts utilised the Kenward-Roger approximation to adjust degrees of freedom and improve accuracy of p-values. Equivalence tests were performed on these trends using pre-specified equivalence bounds defined by the smallest effect size of interest (SESOI) through 'emmeans::test(side = "equivalence")'. This procedure allowed assessment of whether the adaptation trajectories

(linear and quadratic components) of the compensatory moment differed meaningfully between DT and ST conditions. SESOI bounds corresponded to Cohen's conventional standardised effect sizes: d = 0.2 [‘small’ effect (Cohen, 2013)] for the linear trend and d = 0.1 (stricter) for quadratic trend, reflecting the need for capturing higher shape similarity in learning trajectories. These were converted to raw units by multiplying with the model's residual standard deviation. For all statistical tests, an alpha level of 0.05 was used. To control for multiple comparisons across the seven ANOVA outcome measures (GF_{LO}, GF_{max}, GF_{hold}, SM_{avg}, RT, LPD, and RD), p-values for each effect were adjusted using the Holm–Bonferroni procedure (Holm, 1979). Partial eta squared (η_p^2) was reported as effect size for ANOVAs. All data are presented as mean ± SEM unless otherwise specified.

Results

We investigated the interplay of additional working memory load and motor behaviour during a sensorimotor adaptation task. Participants were trained to produce a compensatory moment at lift onset when handling an asymmetrically weighted object, aiming to minimise object roll. This adaptation task was performed concurrently with a verbal working memory task designed to impose additional cognitive load on the participants. Each condition (*DT* and *ST*) included two grasp contexts that either allowed (*uncon*) or prevented (*con*) the choice of contact points.

Cognitive task

Participants maintained high accuracy in the secondary verbal working memory task, successfully recalling the target letter in 97.5% of dual-task trials. Errors were rare and distributed sporadically across subjects, with all participants making 0–1 errors throughout the entire session. This high level of performance indicates that participants actively maintained the cognitive load as instructed.

Compensatory moment trajectory

A polynomial mixed-effects model was fit to the compensatory moment at lift onset (M_{com}), with fixed effects for condition, trial (both linear and quadratic terms), and their interactions, as well as random intercepts and random slopes for trial by subject. The results indicated significant linear and quadratic effects of trial, reflecting systematic changes in compensatory moment over trials. However, differences between the single-task and dual-task conditions, as well as their interactions with the polynomial trial terms, were minimal, suggesting similar trial-wise progression across the task conditions (Table 1).

Table 1. Fixed effects estimates from the polynomial linear mixed-effects model predicting compensatory moment at lift onset (M_{com}). The model includes fixed effects for condition (Single-Task [ST] vs. Dual-Task [DT]), linear and quadratic trial terms, and their interactions. Shown are estimates, standard errors, degrees of freedom, Wald’s t-values, and p-values. Significant effects are indicated with asterisks. Condition was coded such that DT served as the reference category. All coefficients represent differences relative to this group.

Predictors	Estimate	Std.	df	Wald *t*	*P* value

		Error			
Intercept	33.01	10.60	104.94	3.12	<0.01(**)
Condition (ST vs. DT)	-1.50	14.99	104.94	-0.10	0.92
Linear trial (first-order)	18.81	1.85	805.75	10.16	<0.001 (***)
Quadratic trial (second-order)	-0.63	0.08	790.00	-7.45	<0.001 (***)
Condition * Linear trial	-2.45	2.62	805.75	-0.94	0.35
Condition * Quadratic trial	0.11	0.12	790.00	0.95	0.34

Model fit statistics for the mixed model reported **marginal R^2** = 0.277 and **conditional R^2** = 0.446. Note that the fitted curves peaked at approximately trial 15 for DT (174.2 N·mm) and trial 16 for ST (161.7 N·mm) and declined slightly thereafter, reaching 158.6 and 153.2 N·mm at trial 20 (about 9% and 5% below the respective peaks). This decline reflects the absence of a horizontal asymptote in a second-order polynomial rather than a trend in the adaptation trajectory. The observed means showed no such decline (Fig. 3), and over trials 15–20 the mean predicted values (168.5 and 158.9 N·mm) closely matched the observed means (170.3 and 157.7 N·mm). To check that our conclusion did not depend on the polynomial form, we also fitted a model with log(trial) in place of the polynomial terms. This model showed no significant difference between the adaptation trajectories of the two conditions (condition × log(trial): $\beta = -0.95$, SE = 5.63, $p = 0.87$) as well. To directly assess equivalence in adaptation trajectories between the Dual-Task (DT) and Single-Task (ST) groups, equivalence tests were conducted on the linear and quadratic trial terms extracted from the mixed-effects model. For the linear trend (DT, ST), the equivalence test supported that the rates are equivalent between conditions within the predefined bounds, with a significant t-statistic [$t(806) = -3.06$, $p < 0.01$]. Similarly, for the quadratic trend, the test indicated equivalence between conditions, also with a significant t-statistic [$t(790) = -42.998$, $p < 0.0001$].

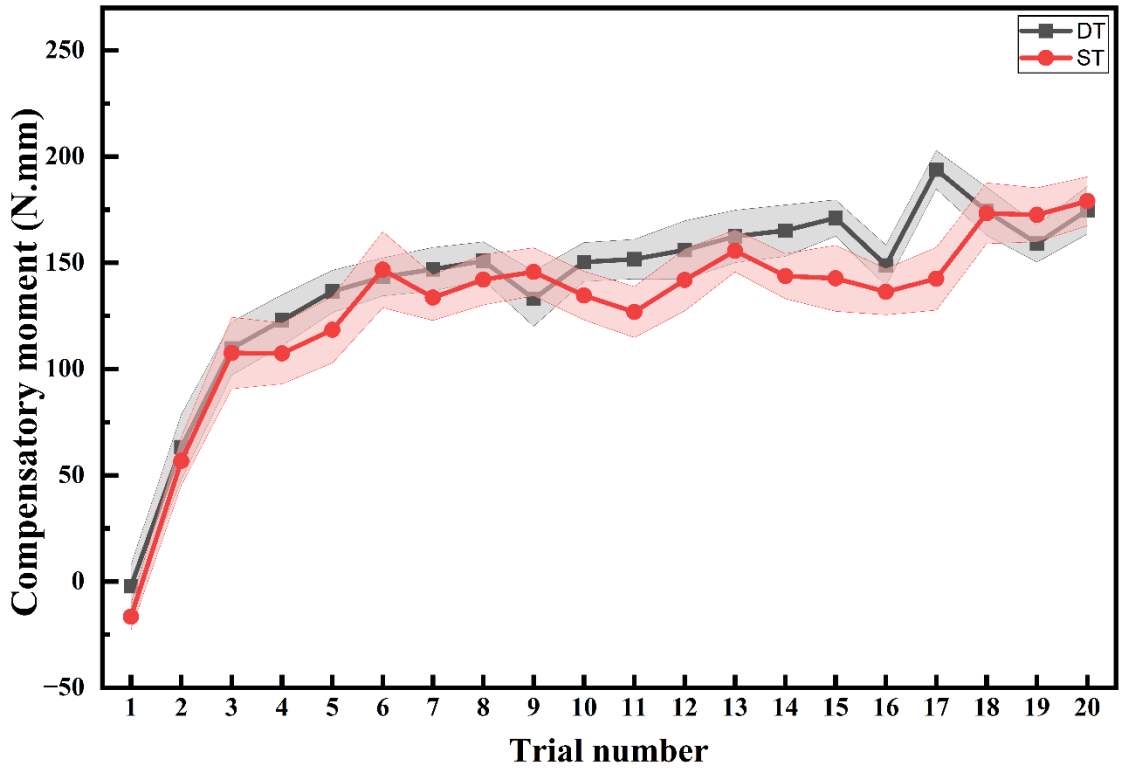


Fig. 3. Trial wise progression of the *compensatory moment (N·mm)* at lift onset across 20 trials for dual-task (DT, black squares) and single-task (ST, red circles) conditions. Shaded areas represent the standard error of the means at each trial. Both groups show rapid initial improvement followed by a plateau indicating acquisition of stable internal representation of the object dynamics. A polynomial mixed model on the compensatory moment showed no significant interaction of the linear and quadratic trends with condition (Table. 1).

1

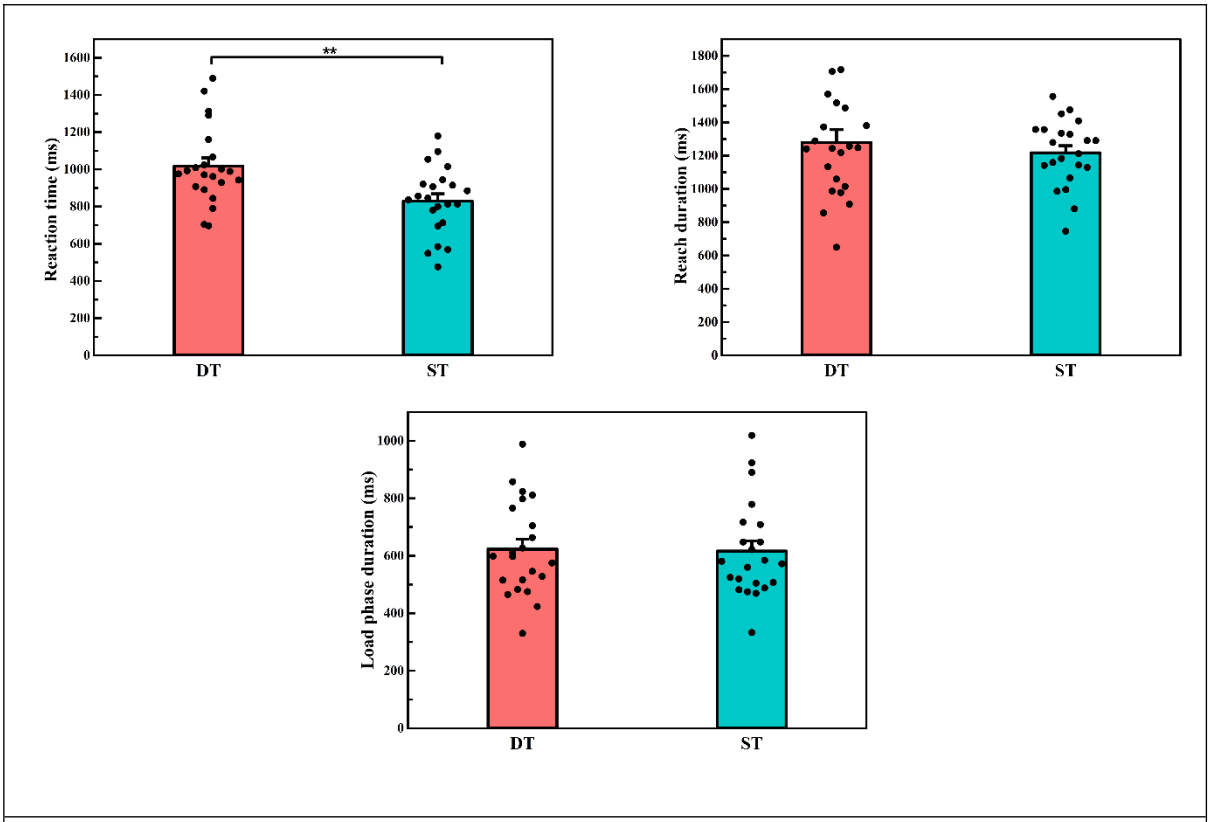


Fig. 4. Across participant means of the *Reaction time (RT)*, *Reach duration (RD)*, and *Loading phase duration (LPD)*. for the experimental conditions DT and ST. The vertical columns and bars indicate the means and the standard errors of means (SE), respectively. Statistical significance is indicated by (**) for $p < 0.01$. RT for dual task was significantly greater than the RT for single task across both contexts. Asterisks indicate uncorrected p-values. All significant effects remained significant after Holm–Bonferroni correction.

Chronometric measures

Reaction times tended to be longer in the dual-task condition compared to the single-task, while loading phase duration and reach duration showed little difference across contexts or interactions between context and condition. Two-way ANOVAs with factors context (*con, uncon*) and condition (*DT, ST*) were conducted on reaction time (RT), loading phase duration (LPD), and reach duration (RD). For RT, there was a significant main effect of condition ($F(1, 40) = 9.860$, $p < 0.01$, $\eta_p^2 = 0.20$), indicating longer reaction times in the dual-task (DT) compared to the single-task (ST) conditions. The main effect of context ($F(1, 40) = 0.544$, $p = 0.465$, $\eta_p^2 = 0.01$) and the interaction between context and condition ($F(1, 40) = 0.038$, $p = 0.847$, $\eta_p^2 = 9.44e\text{-}4$) were not significant. No significant main effects or interactions were found for LPD (context: $F(1, 40) = 2.114$, $p = 0.154$, $\eta_p^2 = 0.05$; condition: $F(1, 40) = 0.018$, $p = 0.893$, $\eta_p^2 = 4.55e\text{-}4$; interaction: $F(1, 40) = 0.032$, $p = 0.860$, $\eta_p^2 = 7.93e\text{-}4$) or RD (context: $F(1, 40) = 0.880$, $p = 0.354$, $\eta_p^2 = 0.02$; condition: $F(1, 40) = 0.505$, $p = 0.481$, $\eta_p^2 = 0.01$; interaction: $F(1, 40) = 0.539$, $p = 0.467$, $\eta_p^2 = 0.01$). After Holm–Bonferroni correction, effect of condition on RT remained significant ($p_{Holm} = 0.013$).

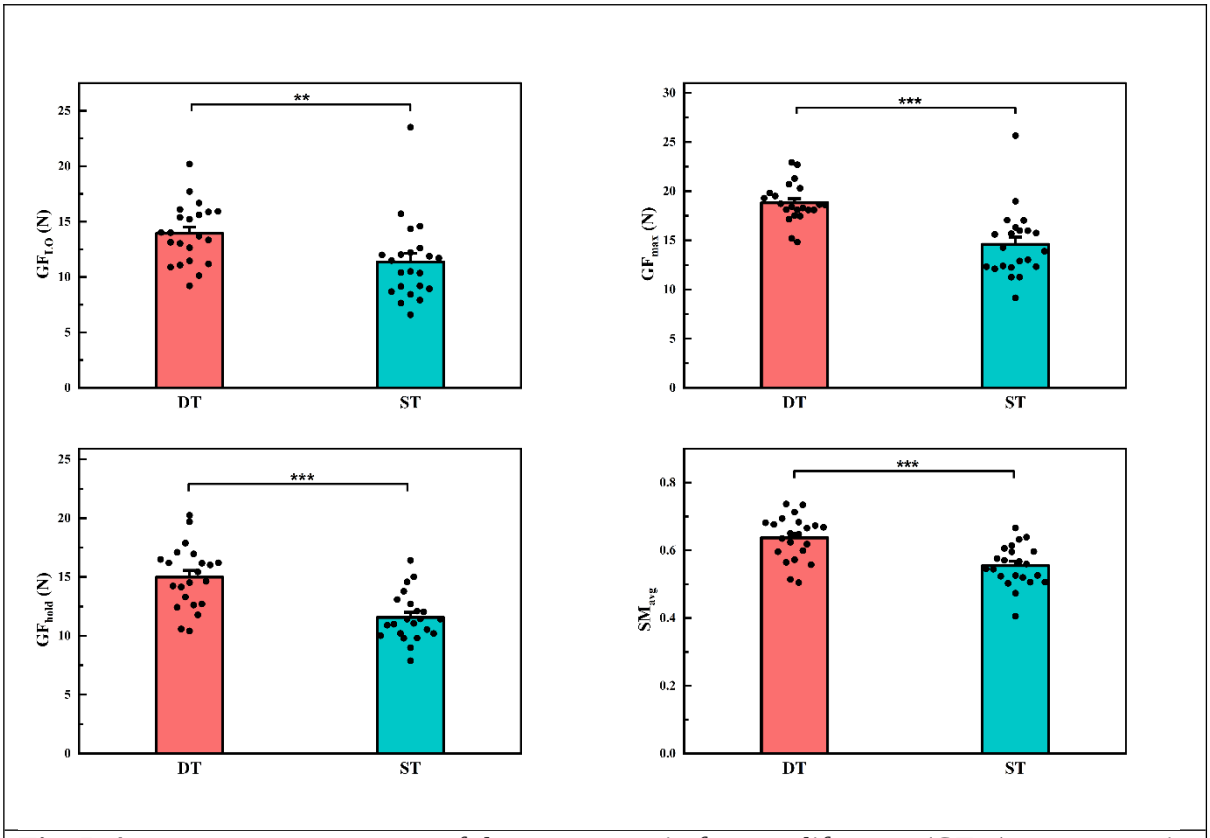


Fig. 5. Across participant means of the *average grip force at lift onset (GF_{LO})*, *average grip force during the hold phase (GF_{hold})*, *average maximum grip force (GF_{max})*, and *average safety margin (SM_{avg})* for the experimental conditions DT and ST. The vertical columns and bars indicate the means and the standard errors of means (SE), respectively. Statistical significance is indicated by (**) for $p < 0.01$ and (***) for $p < 0.001$. Asterisks indicate uncorrected p-values. All significant effects remained significant after Holm–Bonferroni correction.

Motor performance variables

Average grip force at lift onset, maximum grip force, average grip force during the hold phase, and average safety margin all tended to be higher in the dual-task condition compared to the single-task condition, with minimal differences observed across contexts or interactions between context and condition. Two-way ANOVAs on average grip force at lift onset (GF_{LO}), average grip force during the hold phase (GF_{hold}), maximum grip force (GF_{max}), and average safety margin (SM_{avg}) yielded the following results: For GF_{LO}, there was a significant main effect of condition ($F(1, 40) = 7.328$, $p < 0.01$, $\eta_p^2 = 0.15$); no significant main effect of context ($F(1, 40) = 2.359$, $p = 0.13$, $\eta_p^2 = 0.06$) or interaction ($F(1, 40) = 1.298$, $p = 0.26$, $\eta_p^2 = 0.03$). For GF_{max}, a significant main effect of condition ($F(1, 40) = 25.596$, $p < 0.001$, $\eta_p^2 = 0.39$) was observed; no significant main effect of context ($F(1, 40) = 0.262$, $p = 0.61$, $\eta_p^2 = 0.007$) or interaction ($F(1, 40) = 3.292$, $p = 0.08$, $\eta_p^2 = 0.08$). For GF_{hold}, there was a significant main effect of condition ($F(1, 40) = 22.615$, $p < 0.001$, $\eta_p^2 = 0.36$); no significant main effect of context ($F(1, 40) = 1.175$, $p = 0.28$, $\eta_p^2 = 0.03$) or interaction ($F(1, 40) = 2.788e\text{-}4$, $p = 0.98$, $\eta_p^2 = 6.97e\text{-}6$). For SM_{avg}, a significant main effect of condition ($F(1, 40) = 19.788$, $p < 0.001$, $\eta_p^2 = 0.33$) was present; no significant main effect of context ($F(1, 40) = 1.706$, $p = 0.20$, $\eta_p^2 =$

0.04) or interaction ($F(1, 40) = 0.059$, $p = 0.847$, $\eta_p^2 = 1.47e\text{-}3$). After Holm–Bonferroni correction across the seven outcome measures, all condition effects remained significant (GF_{LO}: pHolm = 0.030; GF_{max}, GF_{hold} and SM_{avg}: pHolm < 0.001). Trial-wise profiles of grip force during the hold phase (GF_{hold}) and reaction time are shown in Supplementary Fig. S1. In both conditions, GF_{hold} rose over the first few trials and then declined gradually, and it was consistently higher in DT than in ST. Reaction time showed no systematic trend across trials.

Discussion

The present study investigated how cognitive load interacts with sensorimotor adaptation during dexterous object manipulation in a dual-task paradigm. Specifically, participants learned to generate a compensatory moment at lift onset when lifting an asymmetrically loaded object, with the aim of minimising object roll (Fu et al., 2010). This adaptation task was performed concurrently with a verbal working memory task that loaded the participants' cognitive resources. We hypothesised that the trajectory of sensorimotor adaptation would be impacted by cognitive-motor interference, based on the premise that increased cognitive load could disrupt the multisensory integration processes underpinning such adaptation.

Consistent with previous research and expectations, disruption of the immediate reach–grip–lift motor performance was observed under cognitive load. Among the chronometric measures, reaction time, i.e., the time taken to initiate movement, increased in the dual-task condition, reflecting previous findings that cognitive load delays responses to stimuli (Hesse & Deubel, 2011; Kitatani et al., 2023). This indicates that movement planning and the initiation of complex motor actions are susceptible to interference from concurrent cognitive load (Spiegel et al., 2013; Löhr-Limpens et al., 2022). Note that the observed reaction time delay may reflect a composite of at least two factors, firstly, the 'maintenance cost' of actively holding information in working memory, and the 'task-switching cost' of shifting the focus of attention from the cognitive task to the motor task, with the latter potentially being a significant contributor. Further work will be needed to dissociate these contributions more directly. However, we did not find significant differences in the reach duration or the loading phase duration. The latter result varies from Guillery et al. (2017), who reported that cognitive load increased the duration of the preload phase and, under high load, decreased the duration of the load phase. Since our analysis did not separate the loading phase into preload and load components and instead considered the merged loading phase, these opposite effects would largely cancel out, which may explain why no difference was detectable in our loading phase duration measure **(Fig. 4).** Importantly, and in line with (Guillery et al., 2013, 2017) we found elevated grip forces across all measures viz., grip force at lift onset, maximum grip force, and average grip force during the hold phase, in the cognitive load condition. An increased safety margin in the dual task condition further indicated that the grip force increase was not compensating for a reduction in object friction (**Fig. 5**). Together, these findings corroborate prior work demonstrating that the adjustment of grip force during manipulation is influenced by the availability of cognitive resources, implicating higher-order cognitive control mechanisms.

However, contrary to our primary hypothesis, we found that adaptation to the eccentrically loaded object remained robust, even when participants performed the working memory task in parallel **(Fig. 3)**. In addition, the absence of context effects (constrained vs. unconstrained grasping) was unexpected. We had initially hypothesised greater dual-task costs in unconstrained grasping, expecting participants to simultaneously plan grasp configuration alongside motor execution, thereby increasing resource competition with the verbal working memory task. The lack of difference suggests that grasp point selection may operate via relatively automated, low-level sensorimotor mechanisms that draw minimally on the prefrontal working memory resources taxed by the concurrent verbal task. Returning to the adaptation trajectory itself, which remained robust across DT and ST conditions, we attribute the lack of interference to the nature of our task which contrasts with visuomotor adaptation scenarios. Specifically, we speculate that the discrete, error-driven process in our task may be more robust to cognitive interference than continuous visuomotor adaptations where trajectory corrections must be made throughout the movement. The following paragraphs are dedicated to examining possible explanations for this lack of interference, in light of the principal sensory modalities, i.e., visual feedback and haptic feedback that facilitate the adaptation. Note that while proprioceptive inputs also form part of the somatosensory feedback alongside haptic inputs, proprioceptive afferents exhibit very low sensitivity to mechanical contact events in object manipulation (Johansson & Flanagan, 2009). Therefore, we do not discuss the implication of this modality, as it is likely to have minimal impact on adaptation to object dynamics during manipulation.

The disruptive effects of working memory load on visual processing appear to be highly context-dependent, manifesting predominantly in environments that contain goal-irrelevant distractors competing for attentional resources. Previous research (Lavie & De Fockert, 2005) has demonstrated that increased working memory load impairs top-down attentional control, thereby heightening susceptibility to distraction by irrelevant visual stimuli. Although this work framed these effects as top-down versus bottom-up processes, later research has reconciled this terminology with the well-established distinction between endogenous (goal driven, voluntary) and exogenous (automatic, stimulus-driven) attention (Banerjee et al., 2017). Critically, working memory load has been shown to selectively impair endogenous attentional control while leaving exogenous attention largely intact (Hayward & Ristic, 2013). Our findings are consistent with this view insofar as they suggest that participants' ability to adapt to object dynamics using task-relevant visual feedback, measured here through the compensatory moment at lift onset, remains largely unaffected even under conditions of a concurrent verbal working memory load. Presumably, because our experimental paradigm provided only salient, behaviourally relevant visual feedback without any competing distractors. This absence of irrelevant stimuli reduced the demand for endogenous processing and allowing exogenous attention to effectively prioritise the salient visual feedback, thus preserving the adaptation despite the increased working memory demands. This finding suggests that the detrimental effects of working memory load on complex action and sensory processing arise primarily in contexts carrying distracting stimuli, which require endogenous attentional control to suppress. Conversely, error-based learning processes that depend on clear, task-relevant sensory feedback, and rely on exogenous attentional mechanisms, may remain resilient under cognitive

load. Although as visual feedback and attentional processes were not measured in the present study, this account remains a speculative explanation.

Previous studies have also demonstrated that cognitive load differentially affects various haptic features. For example, (Haghighi et al., 2020) showed that while amplitude and duration perception remain relatively less affected under cognitive load, more complex properties such as waveform, rhythm, and spatio-temporal patterns are significantly impaired. The literature on sensorimotor control further emphasises that tactile feedback at distinct sensorimotor control points plays a critical role in guiding and adjusting object manipulation (Johansson & Flanagan, 2009). This provides a strong foundation for our hypothesis that even subtle disruptions in processing specific haptic cues could affect sensorimotor adaptation, which depends on precise, trial-by-trial integration of multisensory information. By empirically testing this, our study probes whether adaptation is vulnerable to the cognitive interference documented for certain haptic features. The observation that the adaptation remains largely unaffected suggests that, despite cognitive load degrading perception of various haptic features, these deficits may have limited functional impact on adaptive motor control during dexterous object manipulation. It is possible that some complex haptic features remain relatively unaffected, or that the sensorimotor system compensates effectively under dual-tasking conditions, possibly due to redundancy. It is worthwhile to mention that the specific contribution of haptic information was not directly isolated or measured in the present study and therefore, any discussion of modality-specific effects or multisensory integration is necessarily interpretive and based on prior literature showing that cognitive load can interfere with haptic processing (Haghighi et al., 2020).

Our finding that sensorimotor adaptation was preserved under cognitive load, despite motor performance being affected, aligns closely with (Langsdorf et al., 2022) who showed that increased working memory load impaired performance during practice but did not alter the visuomotor adaptation trajectory in posttest measures, with no differential effects on either the explicit or implicit component. This result also echoes a broader body of literature showing the robust resilience of implicit learning to working memory constraints (Janacsek & Nemeth, 2013; Yang & Merrill, 2018). To elucidate, implicit adaptation such as the grip force adjustments involved in object manipulation in our study relies on automatic, error-driven updating of internal models and our findings suggest that it could be relatively insulated from the disruptive effects of working memory engagement, which predominantly affects explicit, deliberate corrections. This dissociation is further supported by neurophysiological evidence showing that working memory engages excitatory networks in frontal cortices (Barbas et al., 2018; Funahashi, 2017) whereas implicit adaptation depends on cerebellar and subcortical circuits that are relatively insulated from such cognitive demands (Israely et al., 2025; Leow et al., 2017). As we did not measure explicit and implicit contributions separately, our interpretation about the functional separation between these contributions remains tentative. Our findings do, however, show that trial-by-trial sensorimotor adaptation can proceed effectively despite concurrent working memory load.

Our findings differ from those of Taylor and Thoroughman (2007, 2008), who found that a concurrent secondary task impaired trial-to-trial adaptation of reaching movements to force

perturbations. In their studies, however, the demanding part of the secondary task was timed to coincide with the movement error. Adaptation was unaffected when an auditory discrimination task occurred before the error, and was most impaired when it overlapped with it (Taylor & Thoroughman, 2007). Similarly, a semantic categorisation task presented at the moment of the perturbation impaired adaptation on the most difficult trials (Taylor & Thoroughman, 2008). In our task, the encoding and recall of the letter sequence took place before the reach and after the object had been replaced **(Fig. 2),** whereas the lift itself, during which the error signal (object roll after lift onset) was available, was performed while participants maintained the sequence in working memory. This task was intended to closely resemble everyday object manipulation, in which information is often held in mind while handling objects. Thus, although maintaining information in working memory during dexterous manipulation does not disrupt trial-by-trial adaptation in our case, interference with adaptation may arise when cognitive processing coincides with the processing of error feedback.

To our knowledge, our study is the first to examine how cognitive load affects sensorimotor adaptation specifically in the context of object dynamics learning during dexterous manipulation. In conclusion, the findings suggest that sensorimotor adaptation to novel object dynamics during dexterous manipulation remains robust under additional cognitive load. However, a few limitations warrant consideration. First, the present task involved adaptation to a single eccentric mass distribution, limiting generalisation to more complex or dynamic scenarios, such as multiple centres of mass conditions. Second, despite instructions to avoid lip movements during the verbal working memory task, covert rehearsal may have occurred, potentially leading to some usage of motor resources in the cognitive task. Third, the present design did not directly manipulate or quantify the separate contributions of visual and haptic feedback, nor did it directly assess multisensory integration. This highlights the need for independently perturbing or measuring visual and haptic signals under cognitive load to test these mechanism level interpretations more directly. Finally, the nature of the concurrent cognitive task warrants consideration. We employed a verbal working memory task to impose cognitive load without directly interfering with the spatial processing required for object manipulation. However, given that dexterous manipulation is inherently spatial, a spatial working memory task (e.g., remembering locations or trajectories) might yield different results. Such a task would likely compete more directly for the overlapping parietal and frontal resources involved in spatial attention and motor planning (Seidler et al., 2012). Consequently, studies utilising spatial cognitive loads may reveal stronger interference effects on sensorimotor adaptation than observed here. Subsequent research should address these limitations by examining adaptation to varied object dynamics and employing methods to monitor or restrict the confounds, alongside neurophysiological investigations, to help elucidate the neural mechanisms supporting our findings. It will also be important to test whether the robustness observed here generalises to older adults, particularly those with measurable cognitive decline.

Author Contributions Statement

Conceptualisation – SD, VSKM; Methodology – SD, VSKM; Formal Analyses – SD; Original Draft – SD; Review and Editing – SD, VSKM.

Data Availability

Data supporting the analyses in this paper can be obtained upon reasonable request to the corresponding author.

Conflict of interest

The authors declare no competing interests.

Acknowledgements

We thank the Department of Science & Technology, Government of India, for supporting this work, vide Reference no.s SR/CSRI/97/2014 & DST/CSRI/2017/87 under Cognitive Science Research Initiative (CSRI) (awarded to Varadhan SKM). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

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