Performing Fitts' tasks in Virtual Reality with and without augmented feedback: a comparison between young and older adults.

Study Protocol and Statistical Analysis Plan

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Abstract

Maintaining cognitive capacities in older adulthood is a growing challenge, making it increasingly important to understand age-related changes in information processing. A well-established motor-cognitive paradigm to study these changes is Fitts' task, which consists of rapid, goal-directed aiming movements under systematically varied accuracy constraints. According to Fitts' Law, movement time (MT) increases linearly with the index of difficulty (ID), yielding an efficiency function (EF) whose slope reflects information processing efficiency (IPE). In real-world laboratory settings, older adults show longer MTs and steeper EF slopes than younger adults, indicating reduced IPE. This decline has been linked to increased cognitive demands, particularly attentional processes during movement deceleration. Fitts' task therefore provides a robust framework to assess changes in motor-cognitive interaction across the adult lifespan.

At the same time, immersive virtual reality (VR) is increasingly used in rehabilitation and research with older adults, making it critical to understand how VR affects motor-cognitive performance. Previous studies suggested that aiming movements performed in VR – especially in three-dimensional space – place higher demands on information processing capacities, which is reflected by longer MTs, more corrective sub-movements, and reduced spatial accuracy compared to real-world performance. These effects appear to be most pronounced for movements along the depth axis, likely due to altered depth perception. While these studies have provided important insights on changes in motor-cognitive demands in VR, they often employed less stringent task implementations, leaving open how well these constraints can be met under immersive conditions. Moreover, to our knowledge, older adults have scarcely been included in existing VR Fitts' studies.

This raises the question of how Fitts' task can be reliably implemented in VR to assess age-related changes in motor-cognitive interactions. We hypothesize that when standard speed-accuracy constraints are applied, accurate execution of Fitts' task in VR becomes challenging and that augmented feedback may be necessary to support reliable performance by compensating for VR-specific visual distortions and limited depth cues. Augmented visual feedback is of particular interest, as it directly targets perceptual limitations inherent to VR.

The present study addresses these issues by examining: (i) how VR affects aiming performance and IPE; (ii) whether Fitts' Law is followed in VR, (iii) whether augmented visual feedback helps to compensate for VR-related performance decline; (iv) whether these effects differ between younger and older adults (18-28 vs. 65-75 years). Results are expected to be available at the time of presentation.

1. Introduction

As global life expectancy increases, preserving brain health and cognitive function in older age has become a pressing scientific and societal priority, as recognized by the WHO (World Health Organization, 2021).

Physical and cognitive training are two established approaches to cognitive enhancement in older adults, both of which have been shown to support brain health and neuroplasticity (e.g., Ball et al., 2002; Cassilhas et al., 2007; Colcombe & Kramer, 2003). More recently, the training of complex movements (CMT) has emerged as a distinct approach to enhance cognitive function (e.g., Niemann et al., 2014; Matthews et al., 2016; Voelcker-Rehage et al., 2010, 2011). "Complex movements" conventionally refer to motor tasks requiring the coordination of multiple degrees of freedom (DoF; Bernstein, 1967). These tasks place high demands on motor control and thereby engage cognitive processes such as attention (Temprado et al., 1999) and inhibition (Temprado et al., 2020). Studies have shown that practicing such tasks yields cognitive benefits – particularly in executive functions like inhibitory control (Torre et al., 2023) and cognitive flexibility (Matthews et al., 2016) – that are distinct from those produced by conventional physical training (Budde et al., 2008; Niemann et al., 2014; Matthews et al., 2016; Voelcker-Rehage et al., 2011). Examples include bimanual (Temprado et al., 1999, 2020), quadrupedal (Matthews et al., 2016), and whole-body coordination tasks (Niemann et al., 2014; Voelcker-Rehage et al., 2010, 2011).

In the present work, we argue that the definition of complexity can be further extended to include tasks that involve not only the coordination of multiple DoF but also performance constraints such as high speed and accuracy demands. This perspective motivates our focus on aiming movements performed in three dimensions within the Fitts' task paradigm.

Unimanual aiming and the Fitts' task paradigm

Fitts' task is a well-established experimental paradigm for studying the speed-accuracy tradeoff in human motor control (Fitts, 1954). In this task, typically performed in one or two dimensions, participants perform rapid, goal-directed aiming movements from a fixed starting point to a target as quickly and accurately as possible (Fitts, 1954; MacKenzie & Buxton, 1992). Although unimanual, these movements involve controlling multiple DoF under strict accuracy constraints and can therefore be regarded as complex movements, engaging cognitive processes such as attention, information-processing speed, and possibly inhibition, with the degree of engagement varying as a function of task difficulty. Task difficulty itself can be systematically manipulated by varying target distance (D) and/or target width (W): increasing D or decreasing W makes the task more difficult. This is commonly quantified by the index of difficulty (ID), which combines D and W into a single value and is defined as:

$$\log_2\left(\frac{2 * D}{W}\right)$$

(Fitts, 1954; Fitts and Peterson, 1964)

To better capture actual performance, effective width (W_e) and effective distance (D_e) are often used instead of nominal W and D (MacKenzie, 2018). While W_e reflects how spread out the movement endpoints are, D_e reflects the average actual distance moved – both of which can differ from the instructed W and D. Using these effective values, throughput (TP) is calculated as ID divided by movement time (MT). TP is a global measure of information processing capacity, which reflects the balance between speed and accuracy. Higher TP values indicate more effective performance, while lower values suggest less efficient processing (MacKenzie, 2018).

According to Fitts' Law, MT increases linearly with ID. This relationship is captured by the so-called efficiency function (EF), which plots MT against ID (see fig. 1). The slope of the EF reflects an individual's information processing efficiency (IPE): steeper slopes indicate that MT increases more sharply with task difficulty, suggesting lower IPE, while shallower slopes indicate more efficient processing.

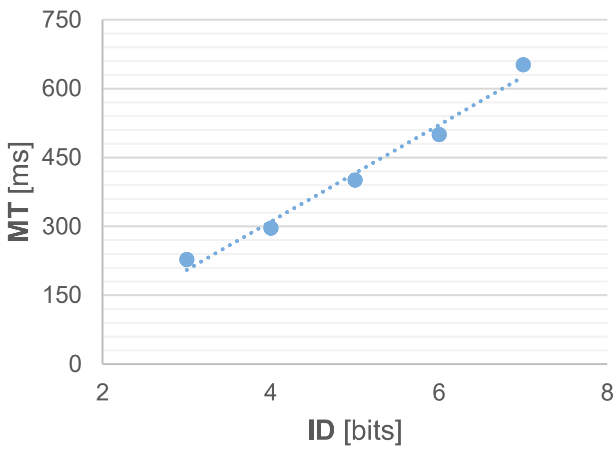

Fig. 1: Representative EF in young healthy adults (data from Sleimen-Malkoun et al., 2013).

Movement kinematics can be divided into acceleration and deceleration phases, commonly defined by acceleration time (AT) and deceleration time (DT), separated by peak velocity (see fig. 2; MacKenzie et al., 1987). The acceleration phase primarily reflects feed-forward, preprogrammed force generation shaped by movement planning and neuromuscular constraints, while the deceleration phase involves feedback-based cognitive control to achieve terminal accuracy (Temprado et al., 2013). It has been found that acceleration time scales with target distance, as longer reaches require greater initial force and planning, whereas deceleration time scales with target width, with smaller targets demanding higher precision and more online corrections during movement termination (MacKenzie et al., 1987; Temprado et al., 2013).

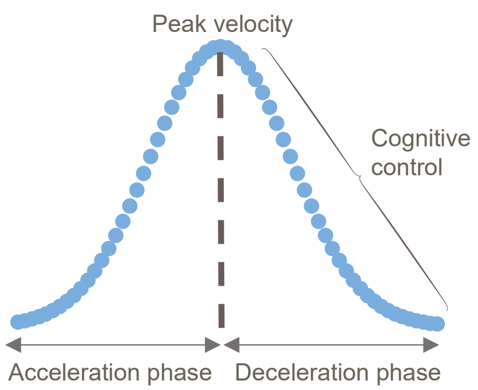

Fig. 2: Typical bell-shaped kinematic profile of an aiming movement accommodating Fitts' task constraints. The profile is separated into acceleration and deceleration phases according to peak velocity. Profile symmetry varies with ID, as well as participants' age or functional status.

<u>Fitts' task and aging</u>

Previous studies on Fitts' task in real-world settings (R) have shown that older adults generally exhibit lower MT and peak velocities compared to younger adults; and, more importantly, they showed reduced IPE, reflected in steeper EF slopes (see fig. 3; Temprado et al., 2013). This decline has been linked to increased cognitive demands (e.g., in terms of attentional and information processing speed requirements), particularly during the deceleration phase (Sleimen-Malkoun et al., 2013; Temprado et al., 2013). Interestingly, a similar slowing of information processing speed has been observed in the Hick-Hyman task, a cognitive task, reinforcing the assumption that EFs can serve as a measure of age-related general slowing in the motor-cognitive system (Sleimen-Malkoun et al., 2013).

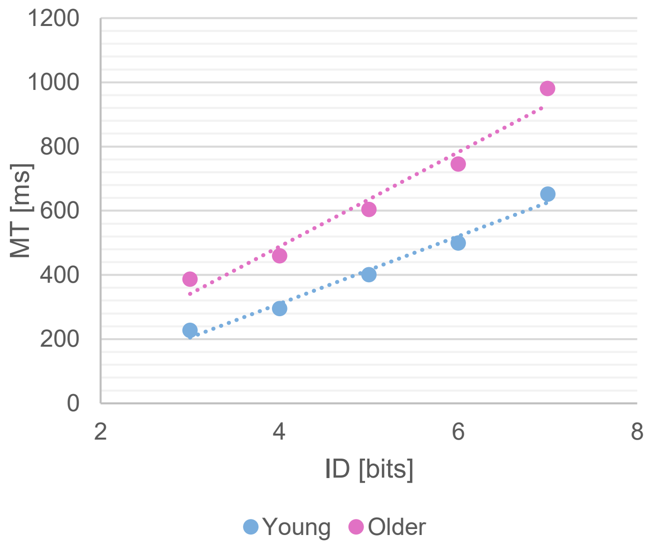

Fig. 3: Representative EFs for younger and older adults. A significant difference was observed between the slopes of the two groups (data from Sleimen-Malkoun et al., 2013).

Fitts' task in 3D

While Fitts' task has traditionally been studied in one- (1D) and two-dimensional (2D) settings (Fitts, 1954; MacKenzie & Buxton, 1992), recent research has extended its application to three-dimensional (3D) environments, which requires the control of additional muscular and articular DoF (Cha & Myung, 2013; Murata & Iwase, 2001; Zeng et al., 2012). Thus, compared to 2D movements, several additional factors have been found to influence MT in 3D, which may, consequently, also affect the linear relationship with ID and the slope of the EFs. Relevant factors include movement direction along the three spatial axes – up/down, left/right, and forward/backward (Cha & Myung, 2013; Murata & Iwase, 2001); the number of DoF involved, such as shoulder rotation, elbow elevation, and wrist compensation (e.g., Morasso, 1983); and the influence of gravity (Jang et al., 2017; Triantafyllidis & Li, 2021). Despite the increased complexity described above, it has generally been shown that Fitts' Law – reflected in the linearity of EFs – also holds for aiming movements in 3D (Cha & Myung, 2013; Murata & Iwase, 2001), though it appears to manifest in longer MTs and potentially steeper EF slopes.

Fitts' task in 3D in virtual reality (VR)

Immersive VR systems are becoming increasingly available for entertainment (e.g., exergames) and are also being integrated into healthcare and rehabilitation (Kirthika et al., 2025), with solutions such as H'ability (H'ability SAS) and VR Essential (ezyGain SAS). As a result, both gamers and patients commonly perform 3D movements to interact with virtual environments, such as reaching, aiming, and selecting virtual objects. Many of these movements correspond to Fitts-like tasks performed in 3D. In this context, VR presents both opportunities and challenges for studying human motor control, and establishing the validity and reliability of Fitts' task in VR environments is crucial. On the one hand, VR facilitates flexible task design, including: (i) manipulation of spatial parameters and informational context (e.g., augmented feedback [FB], structured environments), (ii) gamification of exercises, and (iii) simulation of realistic and ecologically valid motor tasks (Raichlen & Alexander, 2017; Temprado, 2021). On the other hand, VR also introduces unique factors affecting movement control that are absent in R conditions (Barrera Machuca & Stuerzlinger, 2019; Batmaz et al., 2019; Lane et al., 2025; Xiao et al., 2024), namely (i) the presence of visual distortion (Melo et al., 2022) and (ii) the lack of reliable depth cues (Gerig et al., 2018). These changes can affect the multisensory integration process, particularly of visual and proprioceptive signals (Pratviel et al., 2021), which is critical for accurate movement control. Moreover, several studies have shown that when performed in 3D and in VR, movements exhibit more sub-movements than in real-world environments, along with longer MTs (Liu et al., 2009), reduced spatial accuracy and lower overall task performance (Barrera Machuca & Stuerzlinger, 2019; Batmaz & Stuerzlinger, 2022). Although these studies did not systematically analyze EFs, the observed performance patterns suggest that they may be steeper in VR environments (see fig. 4). Notably, these performance differences were found to be particularly pronounced in the anterior-posterior (forward/backward) direction, where movement control depends heavily on depth perception. By contrast, lateral movements are less affected in VR and are typically performed faster and more accurately (Barrera Machuca & Stuerzlinger, 2019; Batmaz et al., 2019).

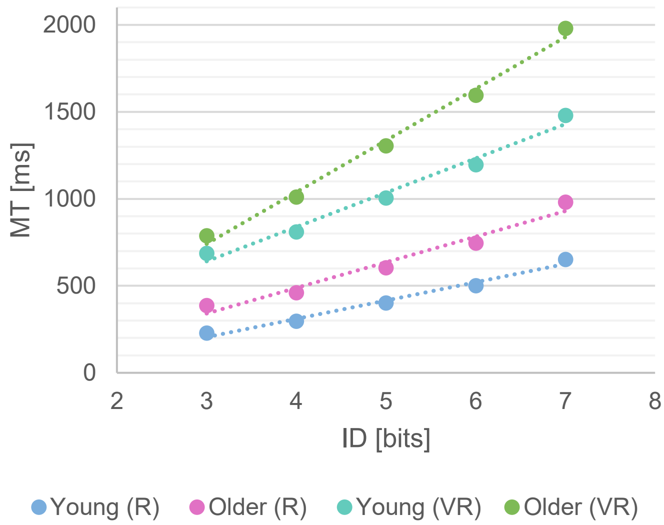

Fig. 4: Representative EFs for younger and older adults in R condition (data from Sleimen-Malkoun et al., 2013), alongside expected EFs for both groups in VR condition. A significant slope difference was observed between young (R) and older (R) participants. EF slopes are expected to be higher and steeper in VR than R conditions. Potentially, an aging effect will be present also in VR conditions, with older adults exhibiting higher EFs than young adults.

This raises the question of whether augmented feedback (FB) can help compensate for visual distortions and limited depth cues in VR, potentially improving performance via enhanced multisensory integration. Augmented FB can be provided through different channels, including visual, auditory, or haptic. Prior work, however, has rarely compared augmented FB to true no-FB conditions. Instead, augmented visual FB was typically provided in all conditions (thus not controlled), with other modalities such as auditory or haptic FB added on top (e.g., Batmaz et al., 2019, 2020; Batmaz & Stuerzlinger, 2022; Kourtesis et al., 2022; Tanacar et al., 2023). Notably, this additional auditory or haptic FB rarely yielded clear performance benefits over augmented visual FB only. The most compelling evidence for the benefit of augmented FB comes from McAnally and Wallis (2024) who explicitly compared augmented auditory FB to a true control condition without any augmented FB (neither visual nor auditory). They showed that auditory error FB significantly reduced performance errors compared to the no-FB condition. Error FB through different channels, such as auditory and visual, conveys similar information. As VR alters visual perception, augmented visual FB may, however, offer specific advantages and therefore it is the focus of the present study. However, its effectiveness remains to be established. Moreover, because errors can take different forms – i.e., overshoot (moving beyond the target), undershoot (falling short), lateral deviation (deviating sideways from the target) or vertical deviation (deviating upward or downward) – it is important to compare the effects of binary FB (indicating success or failure) and more specific FB that indicates the exact nature of each error.

Study rationale and research gaps

Most research on Fitts' task has focused on performance in real-world (R) and 2D settings, primarily measuring information processing speed using MTs and EFs (i.e., Fitts' Law). In this context, cognitive control is required to manage the speed-accuracy trade-off and coordinate multiple DoF, particularly during the deceleration phase. This requires cognitive processes to integrate visual, proprioceptive, and, in sliding movements, haptic information (e.g., friction between the effector and its support; Temprado et al., 2013). However, many questions remain which this study aims to answer:

Fitts' task has increasingly been examined in 3D, but the specific influence of spatial dimensionality on task performance, information processing, and the slopes of EFs remains unclear. Presumably, performing the task in 3D imposes greater cognitive demands, engaging additional attentional and inhibitory resources. In VR, these demands might be further amplified, as multisensory integration is often disrupted. However, the specific effects of such sensory disruptions on task performance and information processing have not been systematically investigated. They may result in lowered task performance (longer MT, higher error rate, and lower TP), less efficient information processing (possibly reflected in steeper EF slopes), and altered movement kinematics (such as disproportionately prolonged DT).

In this context, although augmented error FB might help compensate for VR-induced visual distortions, its effectiveness remains to be determined, notably by comparing the information conveyed across different FB types (i.e., no FB, FB indicating whether the target was hit or missed, and FB indicating the nature of the error; see Methods for details).

Finally, the effects of ageing on unimanual aiming in VR remain unexplored. Indeed, to our knowledge, healthy older adults (HOA) have scarcely been included in existing 3D VR Fitts' studies, despite being a population that could benefit most from VR-based CMT aimed at counteracting motor-cognitive decline.

Building on this rationale, the present study aims to fill these gaps.

1.1 Objectives

The objectives of the present studies are the following:

- To assess whether Fitts' Law holds in 3D immersive VR compared to R conditions when only intrinsic visual FB is available, in both YA and HOA.
  - ➔ RQ1: Does Fitts' Law hold in 3D immersive VR compared to R conditions?
- To determine whether Fitts' Law is maintained in VR under two types of augmented visual FB (global FB and specific FB; see Methods for details), and to compare their relative effectiveness in supporting task performance and the speed-accuracy trade-off.
  - ➔ RQ2: Can augmented visual error FB induce Fitts' Law-like behavior in VR and improve performance, and does feedback specificity matter?
- To compare the performance patterns of YA and HOA across these conditions.
  - ➔ RQ3: How does age affect 3D Fitts' task performance and kinematics?

1.2 Hypotheses

- The R condition is considered as the reference condition in which participants are expected to follow Fitts' Law, with performance producing linear EFs.
- In general, task performance is expected to be higher in R than VR with shorter MT, lower ER, and higher TP. Further, DT is expected to be disproportionately long relative to AT in VR.
- In VR without augmented FB, Fitts' Law may not hold (or at least, it should be nearly flat) since participants might fail to reach targets reliably and be unable to appropriately modulate the speed-accuracy trade-off as a function of ID.
- When providing augmented visual FB in VR, it is expected to improve task performance and to restore Fitts' Law-like behavior, potentially producing higher EF slopes than in R. In this, specific FB is hypothesized to be more effective than global FB, as the greater amount of information should better support an optimal speed-accuracy trade-off.
- Regarding age effects, HOA are predicted to have generally lower performance (higher error rate, longer MTs, lower TP), steeper EF slopes, and disproportionately longer DT. Differences are expected to be amplified in VR due to greater cognitive and sensorimotor demands from distorted sensory input. Furthermore, HOA may benefit more from augmented FB, particularly specific FB, than YA as a greater amount of information may better compensate for age-related declines in cognitive control essential for precise movement termination.

2. Methods

2.1 Participants

A total of 30 participants (women and men) will be recruited, specifically 15 YA (aged 18 to 28) and 15 HOA (aged 65-75). This sample size was determined through an a priori power analysis using G*Power 3.1.9.7 software (for details, see Faul et al., 2007) for a mixed-design repeated-measures ANOVA with two groups and four within-subject measurements (reflecting the between- and within-subject factors described later, i.e., age group and FB conditions). The calculation was based on the primary outcome measure, namely the slopes of the EFs (reflecting IPE). The analysis assumed an alpha level of 0.05, statistical power of 0.80, a medium effect size ($f = 0.26$), a correlation among repeated measures of 0.5, and a non-sphericity correction factor of 1.0. As no VR Fitts' task studies have analyzed EF slopes, to our knowledge, we based our effect size estimate on TP analyses, which is derived from the same underlying variables as EFs (MT and ID) and additionally accounts for endpoint accuracy. Specifically, Batmaz and Stuerzlinger (2001) reported a within-subject interaction of selection technique × auditory FB on TP (partial $\eta^2 = 0.22$, corresponding to $f = 0.53$; converted following Kim, 2016). Because this was a pure within-subject interaction on TP, whereas our primary hypothesis concerns a mixed interaction on EF slopes – including additional between-subject variability – we conservatively halved the effect size for the power calculation. Since this yielded an estimated required sample size of 22 participants, recruiting a total of 30 provides a margin for potential attrition or unusable data and aligns with sample sizes in similar VR studies.

Recruitment for both age groups will take place on a rolling basis over a period of approximately two months (between February and April 2026).

HOA (65 to 75): individuals living autonomously at home through multiple ways:

- In the existing cohort of 'Chair Active Aging' which is a well-established database of approximately 100 HOA (men and women) who have previously expressed interest in participating in research on motor control and physical activity training.
- Through calls for participation in local newspapers and outreach to leisure clubs for seniors in the city of Marseille will be used to broaden the recruitment base.
- Through calls for voluntary participation in the SMUC-Maison Sport Santé of Marseille.
- These strategies are intended to increase inclusivity by reaching individuals outside the existing cohort and to minimize the risk of insufficient enrollment or difficulty assembling a homogeneous sample of HOA.

YA (18 to 28): Recruitment will be made within the student population of the University campus (Luminy Campus in Marseille) through on-campus posters, university mailing lists, and word-of-mouth referrals.

General inclusion criteria

- Aged 18 to 28 (YA group) or 65 to 75 (HOA group)
- Right-handed
- Normal or corrected-to-normal vision (glasses or contact lenses permitted)
- Clear and comfortable vision through the head-mounted display (HMD) during a brief fitting (very bulky glasses may be incompatible)
- No self-reported history of neurological or psychiatric disorders, as confirmed by participant report and cross-checked against a standardized list of relevant medications
- Able to provide informed consent and follow experimental instructions in French or English

Additional criteria for HOA

- Normal cognitive functioning (Montreal cognitive assessment [MoCA] score ≥ 26; Nasreddine et al., 2005)
- No self-reported acute or chronic pain in the dominant arm, shoulder, or elbow that would preclude performing repetitive arm movements in space.
- Self-reported full functional range of motion in the dominant arm (able to extend the arm fully without discomfort or restriction)

Exclusion criteria

- Individuals currently playing video games more than 5 hours/week.
- Uncorrected visual, auditory, or motor impairments that would interfere with task performance.
- Participant height outside the range of 1.50 - 1.80 m.
- Self-reported diagnosis of a neurodegenerative disease (e.g., Parkinson's disease, Alzheimer's disease)
- Self-reported use of medications known to significantly affect cognitive or motor function (a list of relevant medications will be presented during screening).
- Cervical pain that could preclude wearing the VR headset during the full duration of the experimental session.
- Self-reported history of severe motion sickness or vestibular issues that could be exacerbated by VR exposure

- High susceptibility to cybersickness, as assessed via the Visually Induced Motion Sickness Susceptibility Questionnaire (VIMSSQ) which was developed specifically for pre-exposure screening; cut-off: ≥ 12 (Golding et al., 2021; Golding & Keshavarz, 2025).
- Individuals for whom the headset cannot be properly adjusted, e.g., due to an interpupillary distance (IPD) outside the adjustment range of the HMD (i.e., <53 mm or >75 mm).

Note: All health-related criteria above are based on self-report only. No medical examination or physician confirmation will be conducted, as the study involves minimal risk and a non-invasive motor task.

2.2 Experimental protocol

Each participant will complete the study in four successive phases: an initial information process, followed by consent collection seven days later, the data acquisition phase (conducted between days 8 and 10), and a final voluntary information session (see fig. 5).

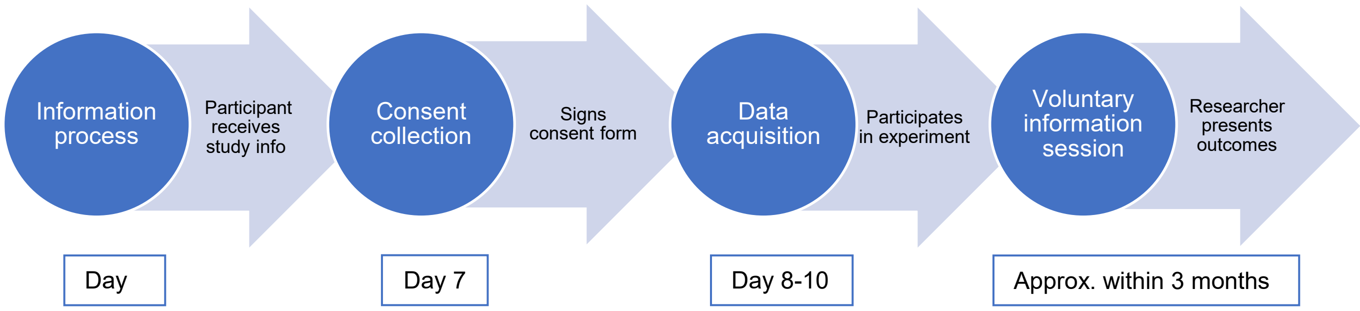

Fig. 5: Overview of the participant procedure and timeline, illustrating the four consecutive study phases.

Information process

During the information process, participants will be provided with comprehensive details regarding the study's purpose, procedures, potential risks and benefits, data handling, and their rights, including the right to withdraw at any time without consequences. If they wish, participants will also have the opportunity to view the experimental setup, including the VR equipment, and briefly try it out. They will then have seven days to consider their participation before providing formal written consent.

Description of the task

Participants will perform a 3D Fitts' task with their dominant right hand, reaching with a handheld controller from a fixed start sphere to a target positioned along the body's sagittal midline. The target will be placed 32 cm forward (anterior-posterior) and 24 cm upward (vertical) from the start position, yielding a resultant movement distance of 40 cm according to Pythagoras' theorem $a^2 = b^2 + c^2$. This distance will at most correspond to about 80% of maximal forward reach.

Apparatus and set-up

Participants will be seated comfortably against a backrest in front of a table throughout the whole experiment, with chair height and apparatus position adjusted individually so that the start sphere is aligned to an ergonomically optimal desk height, comparable to that used for writing. Feet will be positioned flat on the floor; with a footrest used when necessary to maintain this posture. Movements will be performed using a handheld controller tracked by the HMD's built-in system. The HMD will be worn in all conditions: in the R condition, participants will view the physical apparatus through passthrough mode, while in VR, they will see a visually identical virtual replication. Participants will only use their dominant right hand. Before each aiming movement, the right hand will be rested on the table while pointing at the start sphere.

In the R condition, the start sphere will be represented by an open frame mounted on a thin rod on the table in front of the participant. The frame outlines a partial spherical contour that indicates the full size of a sphere (following Barrera Machuca & Stuerzlinger, 2019) and is oriented partly toward the target and partly upward, allowing the intended anterior-posterior and upward toward the target without contacting a solid surface. The target will use the same open-frame spherical design, but with its opening oriented toward the participant and slightly downward, enabling participants to move into the sphere without touching its surface. Both start and target structures will be fabricated from lightweight 3D-printed plastic (2 to 3 mm thickness) with rounded edges. Target diameters will correspond to the W values while the start sphere will have a medium diameter of 7 cm.

In the VR condition, the set-up is visually and spatially replicated (see fig. 6). The start and targets are represented as full grey spheres with a grid-like surface, making their 3D structure visible. Because there are no physical surfaces in the virtual environment, this set-up again allows participants to perform the intended anterior–posterior and upward movements freely.

Material

- HMD: Meta Quest 3 (weight: 515 grams)
- Handheld controllers: Meta Quest Touch Plus
- Sampling frequency: 120 Hz
- Tracking system: In-built
- Software: Unity 6000.0.37f
- Computer system: Windows 11 (64-bit) PC with Intel® Core™ i5-13500H processor, 16 GB RAM, and NVIDIA RTX 4060 GPU

The equipment is commercially available and non-invasive.

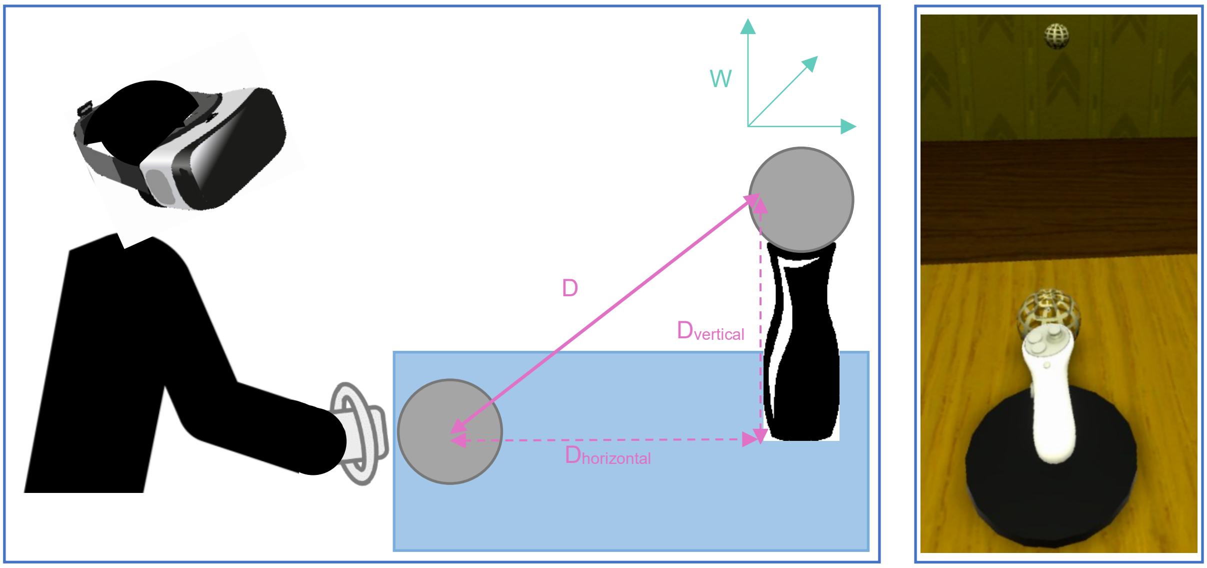

Fig. 6: Experimental set-up and participant view. Left: Schematic side view of a participant in the VR condition. W represents the 3D extent of the target (x-, y-, z-axes), and movement distance is defined as $D = \sqrt{D_{horizontal}^2 + D_{vertical}^2}$. In R condition, the start sphere is an open frame partially outlining the full target size, allowing unobstructed movement toward the target. Right: Example of the virtual environment as seen by participants, showing the controller, the start, and the target itself.

Manipulation of task parameters

- *Task difficulty*

ID will be manipulated via target width (W = 14.1 cm, 7.1 cm, 3.5 cm, 1.8 cm), yielding IDs of 2.5, 3.5, 4.5, and 5.5 bits. Each trial will begin with the controller tip resting on the start sphere. Participants will move as quickly and accurately as possible toward the target, remaining inside the target sphere continuously for 0.6 seconds.

- *FB conditions:*
  - **VR-intrinsic (VR-I).** The immersive virtual setup will be presented without augmented FB about whether targets were hit correctly (or not); participants will rely on intrinsic FB only.
  - **VR-augmented global (VR-AG).** Augmented visual error FB will indicate target entry and trial outcome. Generally, the target turns blue when entered. A successful trial is confirmed when participants remain inside for 0.6s, after which it turns green. For an error, the target turns red; either directly from grey if never entered, or after briefly turning blue if entered and then exited. Alternative colors will be used as needed to accommodate participants with color deficiencies.

- **VR-augmented specific (VR-AS).** In this condition, augmented visual error FB will further indicate the type of error. Overshoots trigger a written message reading ‘too long’, undershoots display ‘too short’, lateral deviations show a message of either ‘error to the right’ or ‘error to the left’, and vertical deviations show a message of either ‘too high’ or ‘too low’.

- *Age groups:*
  - YA (18 to 28 years)
  - HOA (65 to 75 years)

Thus, the study design results in a 3-way mixed factorial design with two within-subject factors (FB condition and ID) and one between-subject factor (age group).

Prior to data recording, participants will complete a familiarization phase in the VR-AS condition, which offers the highest informational value by encompassing all functionalities included in the study. Participants will perform practice trials at IDs 3 and 5 (D = 40 cm; W = 10.0 cm and W = 2.5 cm, respectively), with the order of IDs counterbalanced. Participants will complete as many trials per ID as needed until they feel they have a sufficient understanding of the task, the experimental set-up, and the materials. After each condition, participants will provide a brief motion sickness rating using the Simulator Sickness Questionnaire (SSQ; Kennedy et al., 1993) and have a short break (about 60 s, longer if needed). The main experiment will consist of 120 trials per participant (3 FB conditions × 4 IDs × 10 trials). Trials will be organized into blocks of 40, each comprising four consecutive runs of 10 trials at a single ID (e.g., 10 trials at ID 3, then ID 4, etc.). The order of IDs within each block will be randomized, and the condition order will be counterbalanced across participants using a Latin square design.

<u>Measurement</u>

The motion tracking system of the Meta Quest 3 will be used to capture 3D positional data of the handheld controller throughout each trial (nominal sampling frequency = about 120 Hz). To ensure that only intentional movements will be captured, thresholds were defined for movement onset and offset: Movement onset was defined as when the controller speed exceeded 12.5 cm/sec in a single frame, and movement offset occurred after the controller remained below this threshold for at least 0.6 sec. These thresholds were determined through pilot testing. MT was defined as the time elapsed between movement onset and offset.

Further performance metrics will be computed based on the recorded positional data and MT:

- Error rate, calculated as the proportion of missed targets relative to total number of trials
- W_e, calculated from the dispersion of movement endpoints relative to the target center
- D_e, calculated from the actual movement distance relative to the starting point
- Peak velocity, identified as the maximum velocity reached during the movement for each trial
- AT and DT, extracted from the velocity profile of the movement
- TP, computed based on the effective ID (ID_e) and MT
- EFs, computed by performing linear regressions of MT, AT, and DT against ID

After completing each experimental condition, participants will rate their perceived cognitive effort using the 9-point Likert-type Paas scale developed by Paas et al. (1994, 2008) as well as their perceived exertion using Borg-CR10 scale (Borg, 1982, 2008).

<u>Outcomes</u>

The primary outcome is the comparison of EF slopes across age groups and FB conditions. Secondary outcomes include the quality of EF fits (R^2 values) and the effects of FB condition, ID, and age group (and their interactions) on performance metrics: MT, AT, DT, error rate, and TP.

<u>Duration</u>

Each participant will take part in one experimental session lasting approximately 75 minutes, with short breaks between blocks as needed.

Tab. 1: Overview of experimental procedure per participant

Measure	**Timeline**

Instructions	5 minutes
Familiarization	15 minutes
Experimental trials	50 minutes
Post-experiment debriefing	5 minutes

Data collection is scheduled to take place over a period of approximately three months, beginning upon approval from the CERSTAPS ethics committee. The study is set to start in January 2026 and conclude by April 2026. Recruitment and testing will be carried out on a rolling basis throughout this period, depending on participant availability. After data collection is completed, the data will be analyzed, and participants will be invited to an information meeting where the study's aims and findings will be presented and discussed. This meeting will also offer an opportunity for participants to ask any remaining questions. The study results will subsequently be prepared for publication in a peer-reviewed scientific journal. See fig. 7 for further illustration.

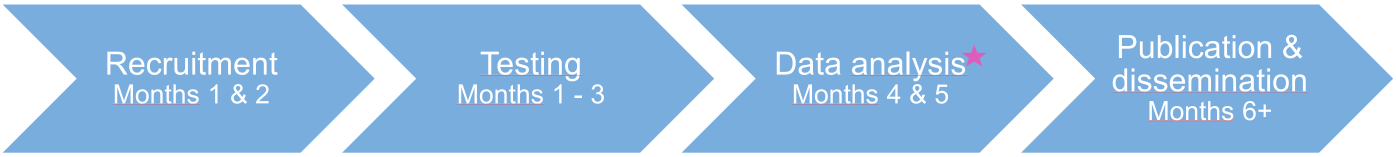

*Fig. 7: Study timeline and dissemination flow. * Refers to the voluntary information session with participants.*

2.3 Data analysis

All statistical analyses will be conducted using Python, with an alpha level of 0.05 and reporting of effect sizes where appropriate.

Fitts' Law verification

To verify whether Fitts' Law holds across all conditions, linear regressions will be performed for each participant and FB condition, relating MT, AT, and DT (dependent variables) to ID (independent variable). For each regression, the slope, coefficient of determination (R^2), and p-value will be extracted to evaluate model fit and statistical significance.

Analysis of EF slopes (primary outcome)

To evaluate the influence of FB condition and age group on the slope of the EFs, i.e., on IPE, a 2-way mixed-design repeated-measures ANOVA will be conducted separately for the EF slopes of MT, AT, and DT. The dependent variables are the EF slope values derived for each participant and condition by regressing MT, AT, and DT against ID. The independent variables include FB condition (4 levels) as within-subject factor and age group (younger vs. older adults) as a between-subject factor. Main effects, interaction, and post hoc comparisons will be reported.

Analysis of performance metrics (secondary outcome)

To explore how age group, task difficulty, and FB condition influence performance, a 3-way repeated-measures ANOVA will be conducted on raw performance metrics. The dependent variables are MT, AT, DT, error rate, and TP. The independent variables include ID (4 levels) and FB condition (4 levels) as within-subject factors and age group (young vs. older) as a between-subject factor. The analysis will test for main effects and all possible two-way and three-way interactions. Significant effects will be further explored using post hoc comparisons.

Analysis of subjective cognitive load and physical exertion

To compare the subjective cognitive and physical exertion across FB conditions, a 2-way repeated-measures ANOVA will be conducted on Paas and Borg scores as dependent variables. The independent variables include FB condition (4 levels) as within-subject factor and age group (younger vs. older adults) as a between-subject factor. Main effects, interaction, and post hoc comparisons will be reported.

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