Replication Study

Revisiting How Display Layout and Visual Delay Shape Weight Perception in Augmented Reality Extended Displays

🎤Yuta Kataoka[*1], Hayato Tanabe[*1], Satoshi Hashiguchi[*1], Fumihiko Nakamura[*1], Fumihisa Shibata[*1], Asako Kimura[*1], and Shohei Mori[*2]

[*1] Ritsumeikan University [*2] VISUS, University of Stuttgart



VRST 2026 Sendai, Japan November 16 -18

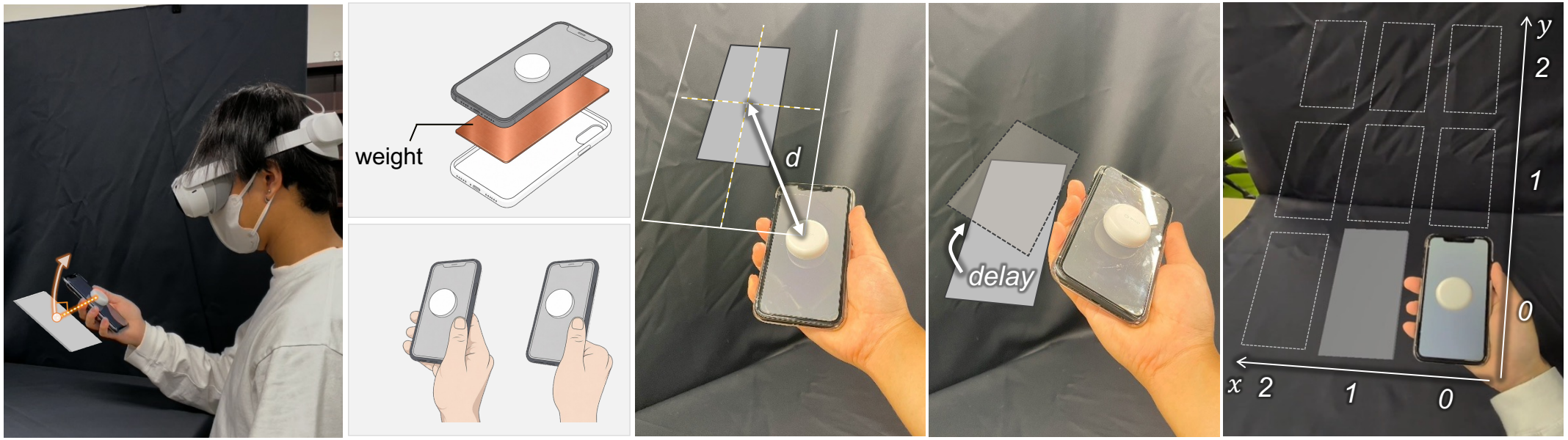
RITSUMEIKAN

University of Stuttgart Germany

VISUS VISUALISIERUNGSINSTITUT DER UNIVERSITÄT STUTTGART

Brief Summary

We revisit how display **layout** and visual **delay** affect perceived weight in AR Extended Displays (AREDs)*

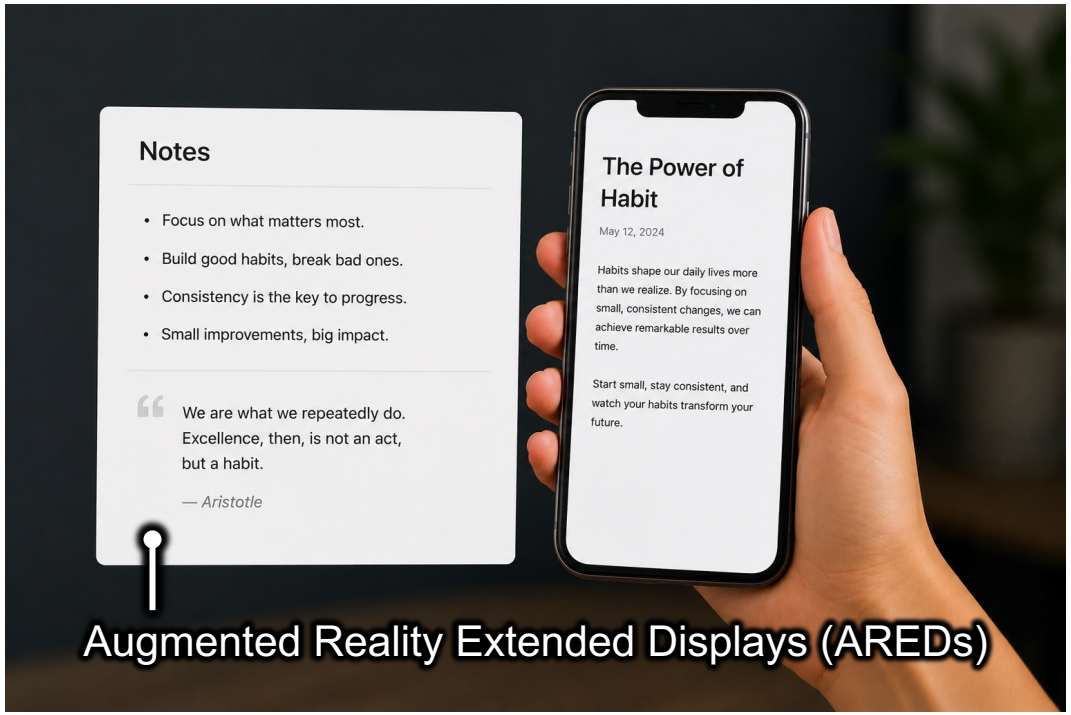


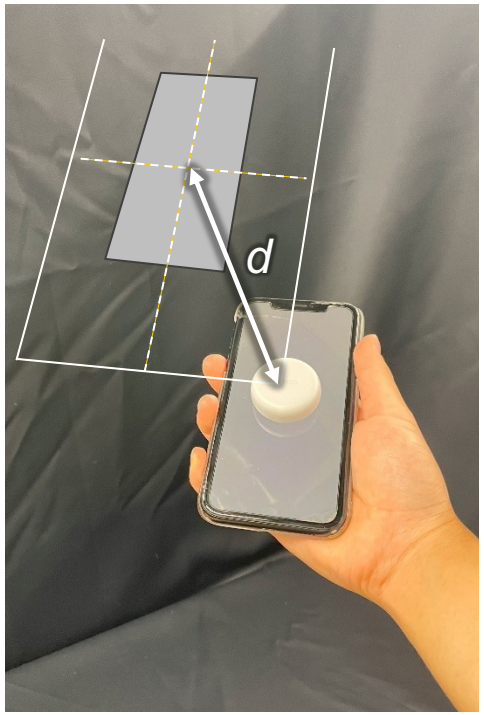
- Findings
  - Farther virtual displays felt lighter (*replicate* layout effect).
  - Weight ratings peaked around 0.30 s of delay and then decreased (*not replicate* delay effect).

* S. Mori, Y. Kataoka and S. Hashiguchi, “Exploring Pseudo-Weight in Augmented Reality Extended Displays,” 2022 IEEE VR, pp. 703-710, 2022.

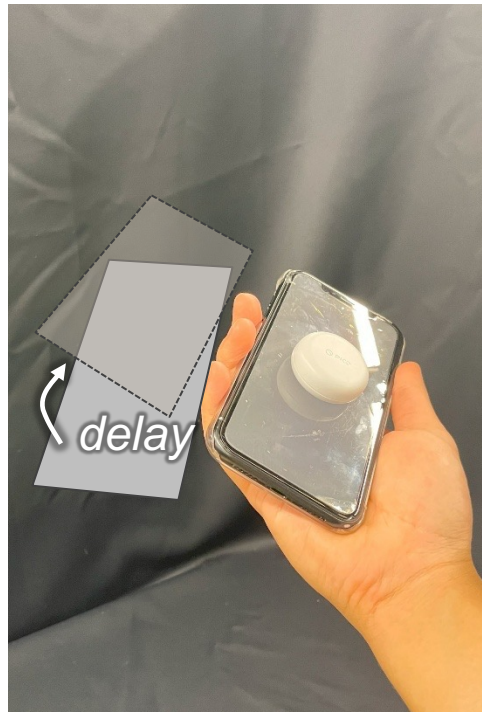
Background: AR Extended Displays

- Device-locked virtual screens extend the workspace around a handheld device.
- Visual **layout** and response **delay** can change the device's perceived weight.



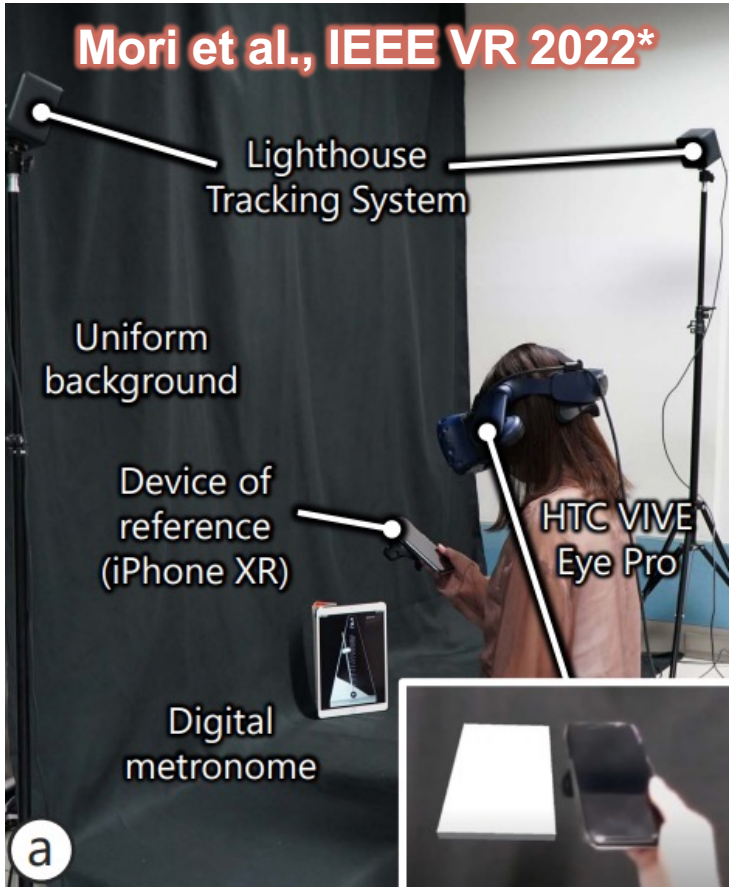


Display layout



Visual delay

Research Question





Research Question: Do the **layout** and **delay** effects replicate with contemporary AR hardware?

* S. Mori, Y. Kataoka and S. Hashiguchi, “Exploring Pseudo-Weight in Augmented Reality Extended Displays,” 2022 IEEE VR, pp. 703-710, 2022.

Replication Comparison

Sendai, Japan
November 16 -18
VRST 2026

Same layout and delay conditions, updated hardware, and a larger sample.

	Original	Our replication
HMD	VIVE Pro (2880 x 1600, 555 g + cable)	PICO4 Ultra (4320 x 2160, 580 g, standalone)
Camera latency	Approx. 0.30 s	Approx. 0.05 s
Tracker	89 g	15 g
Added delay	0, 0.15, 0.30, 0.45, 0.60, and 0.75 s	←
Device	iPhone XR	←
Sample size	*N* = 11 (layout) and *N* = 8 (delay)	*N* = 22



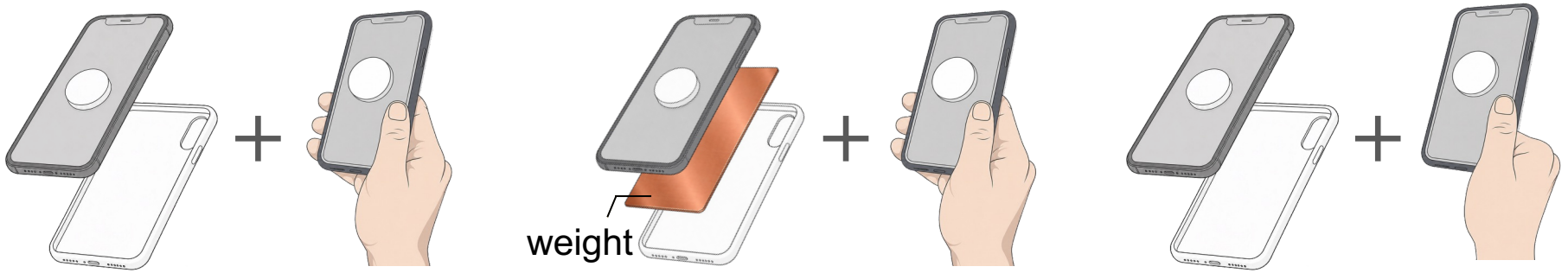



Image sources: HTC VIVE (vive.com) , PICO (picoxr.com)

Experimental Overview

One replication and two follow-up experiments on device mass and grip style.

	Experiment 1	Experiment 2	Experiment 3
Purpose	Baseline replication	Weight-matched	Grip-matched
Device mass	230 g	**314 g**	230 g
Grip	One-handed	One-handed	**Thumb–forefinger**
Conditions	Layout + delay	Layout + delay	Delay



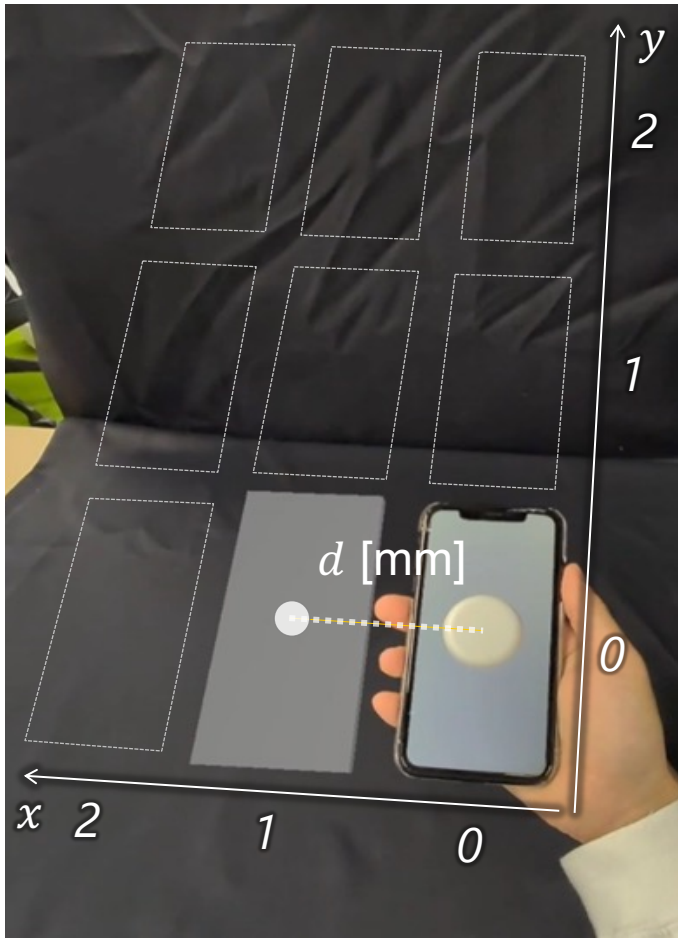
Experimental Setup

- PICO 4 Ultra + PICO Motion Tracker; iPhone XR as the physical anchor
  - Uniform color AR stimulus
- Cyclic wrist motion at 80 bpm
- Magnitude estimation: Reference (5 s, rating = 100) → Test (5 s) → Rating

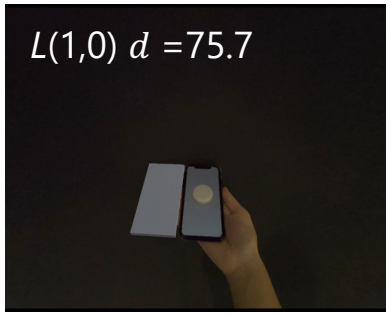


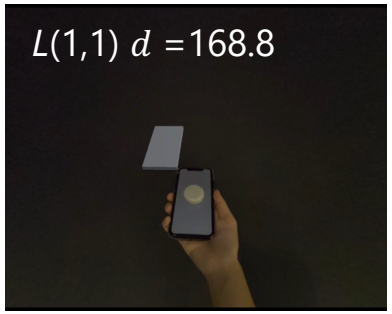
Experimental Conditions

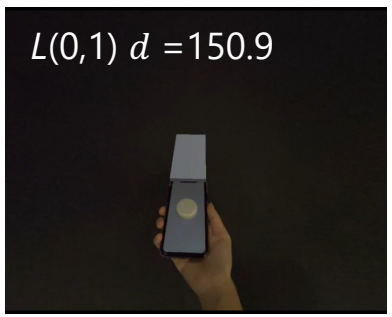
Layout and delay were tested in separate sessions.



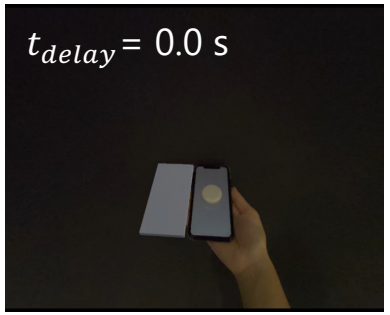
Layout (3 × 3 pos)

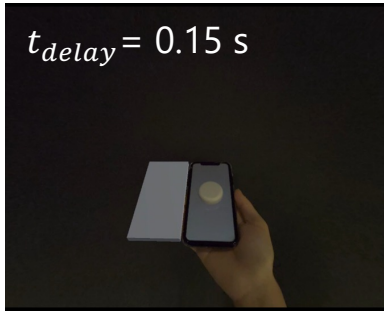






Delay (6 levels)

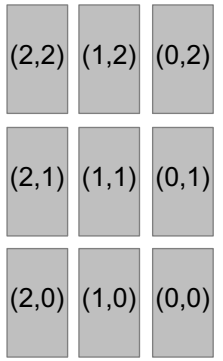






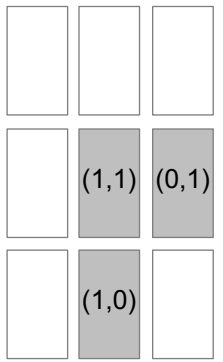
Experiments 1, 2

Layout



9 trails

Delay

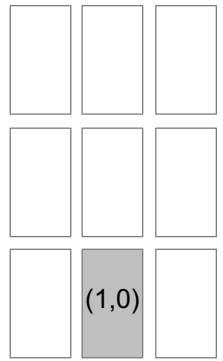


18 trials

- 3 pos (dir)
- 6 delays

Experiment 3

Delay

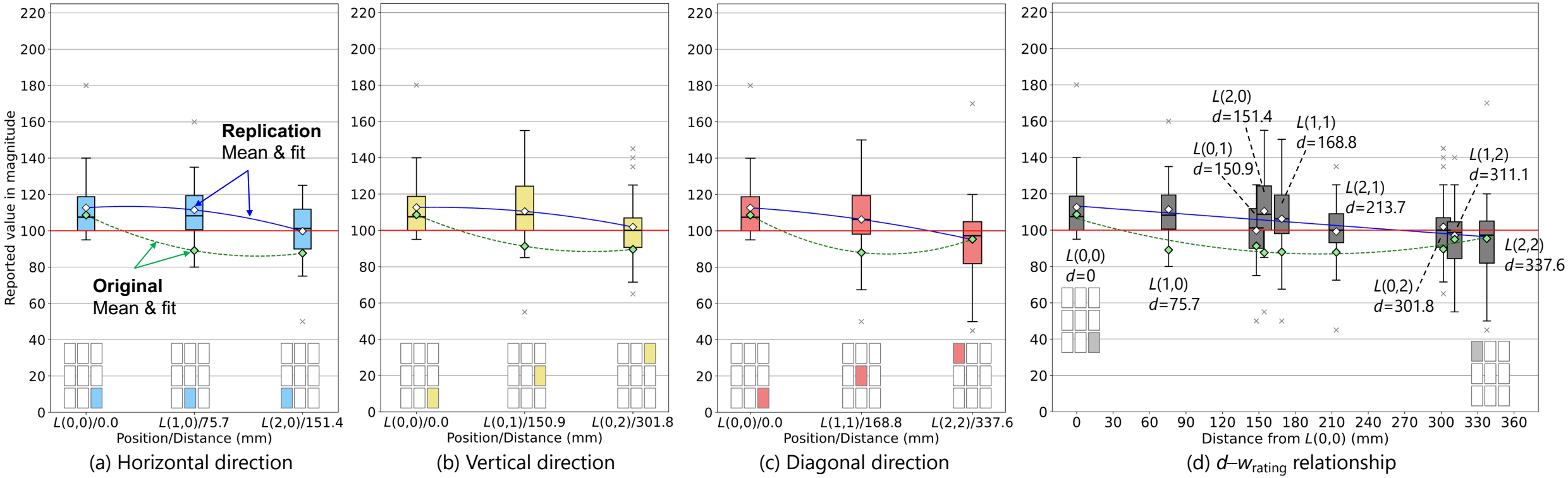


6 trials

- 1 pos (dir)
- 6 delays

Experiment 1: Layout Results

- Nine display locations in a 3 × 3 grid.
- Perceived weight decreased with distance; no significant direction effect.

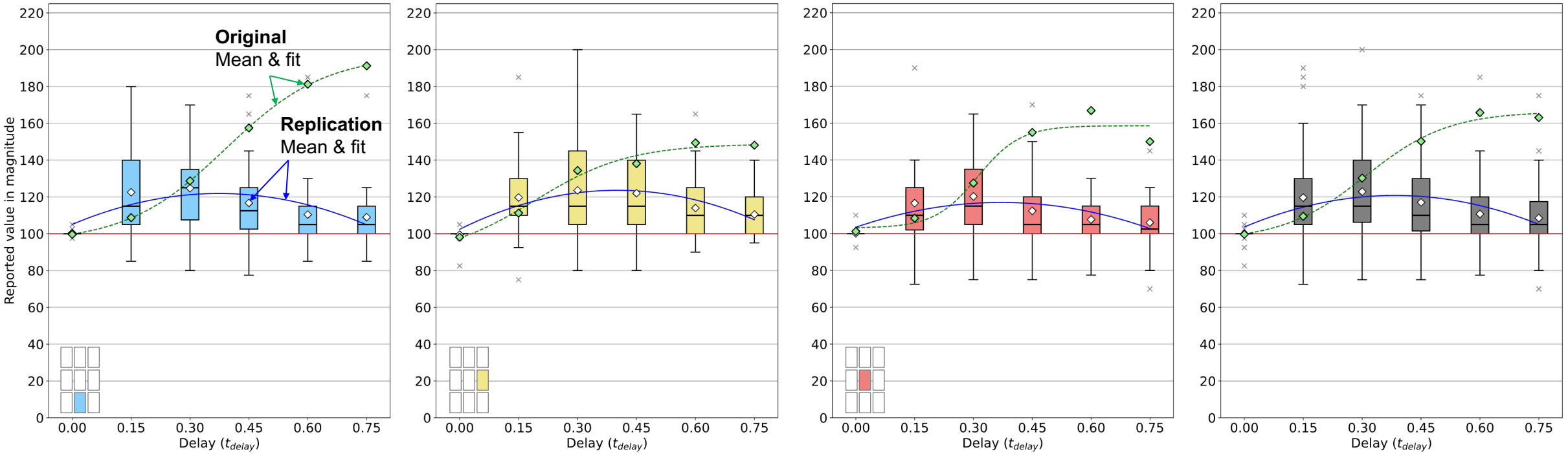


(a) Horizontal direction (b) Vertical direction (c) Diagonal direction (d) d–w_{rating} relationship

Farther display = Lighter device (replicated)

Experiment 1: Delay Results

- Six added delays (0–0.75 s) × three locations.
- Observed mean ratings peaked around 0.30 s and declined at longer delays.

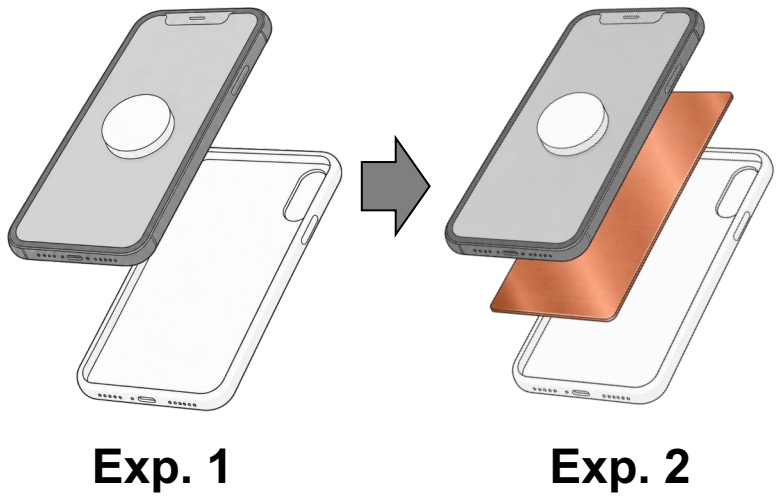


(a) Horizontal direction (b) Vertical direction (c) Diagonal direction (d) t_{delay}–w_{rating} relationship

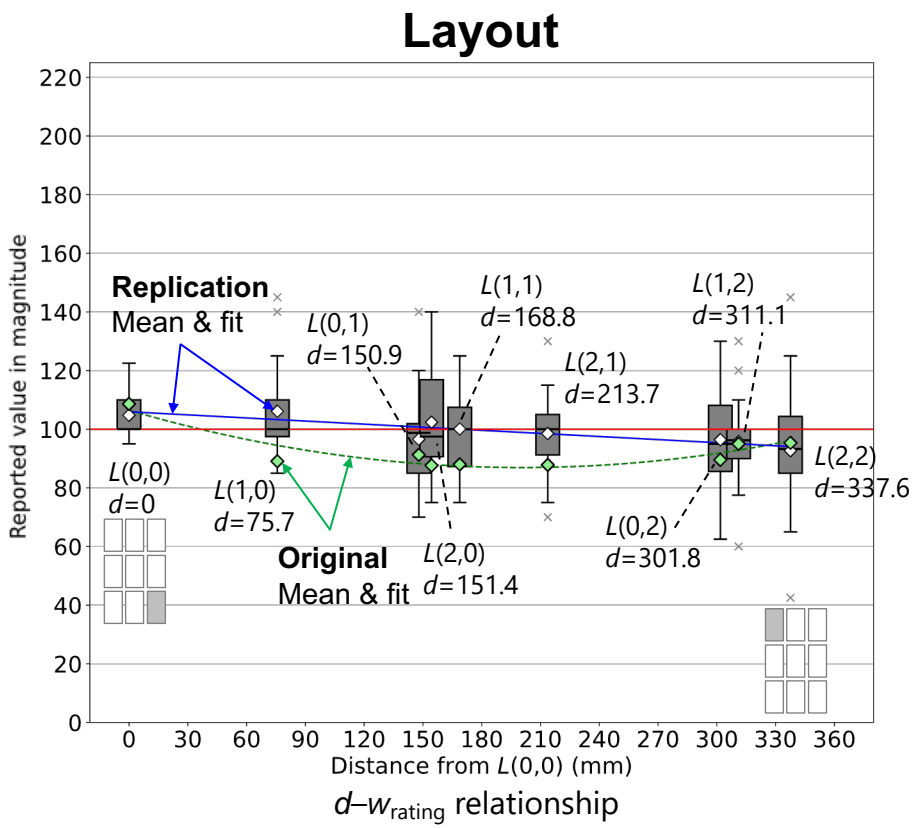
More delay ≠ Continuously heavier (not replicated)

Experiment 2: Weight-Matched Replication

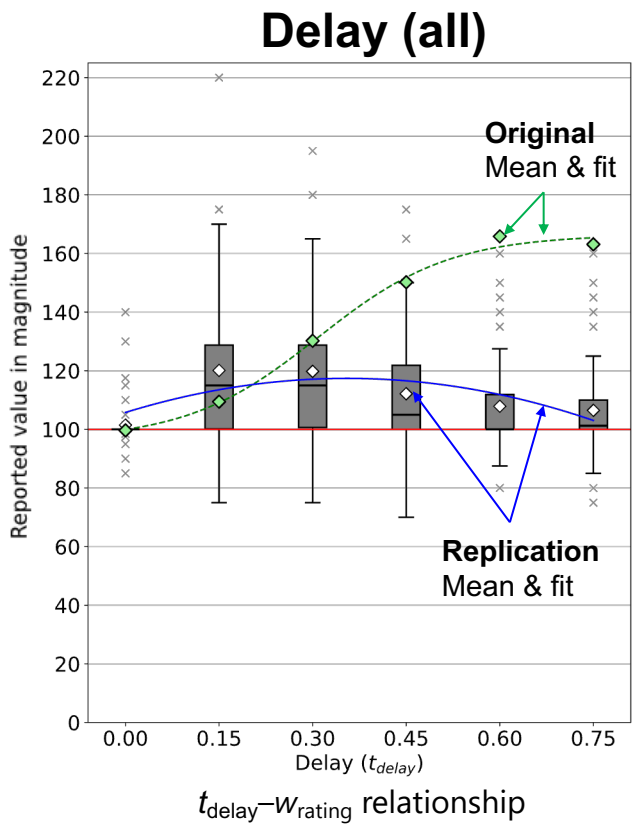
- Added a copper plate: 230 g to 314 g, matching the original device mass.
- Kept the one-handed grip and procedure; the non-monotonic pattern remained.



Exp. 1 Exp. 2



d–w_{rating} relationship

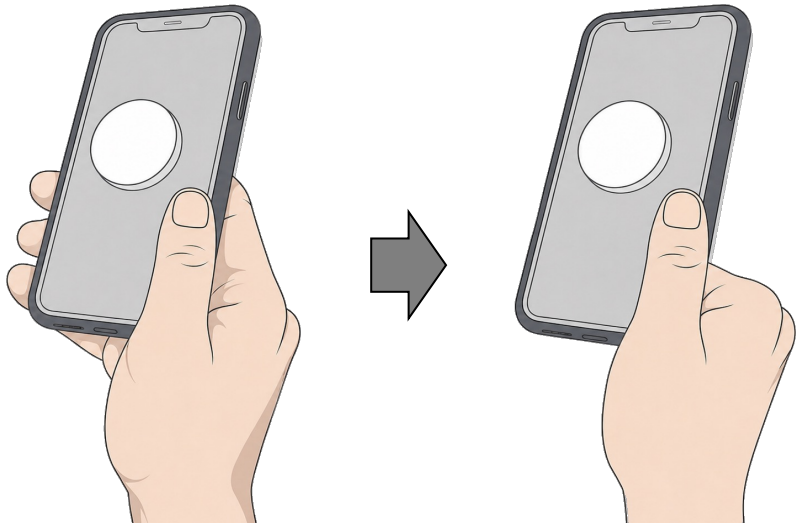


t_{delay}–w_{rating} relationship

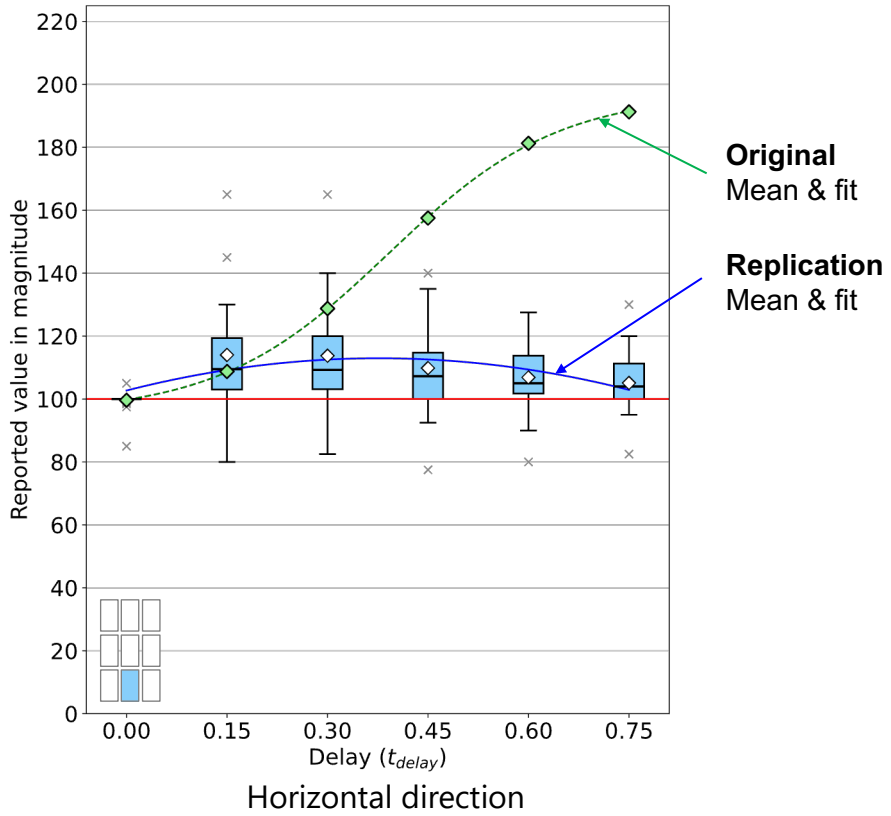
Matching device mass did not restore the original delay pattern

Experiment 3: Grip-Style Validation

- Matched the original thumb–forefinger grip, retaining the 230 g device.
- The non-monotonic pattern persisted across six delays at the horizontal location.



Exp. 1 and 2 Exp. 3

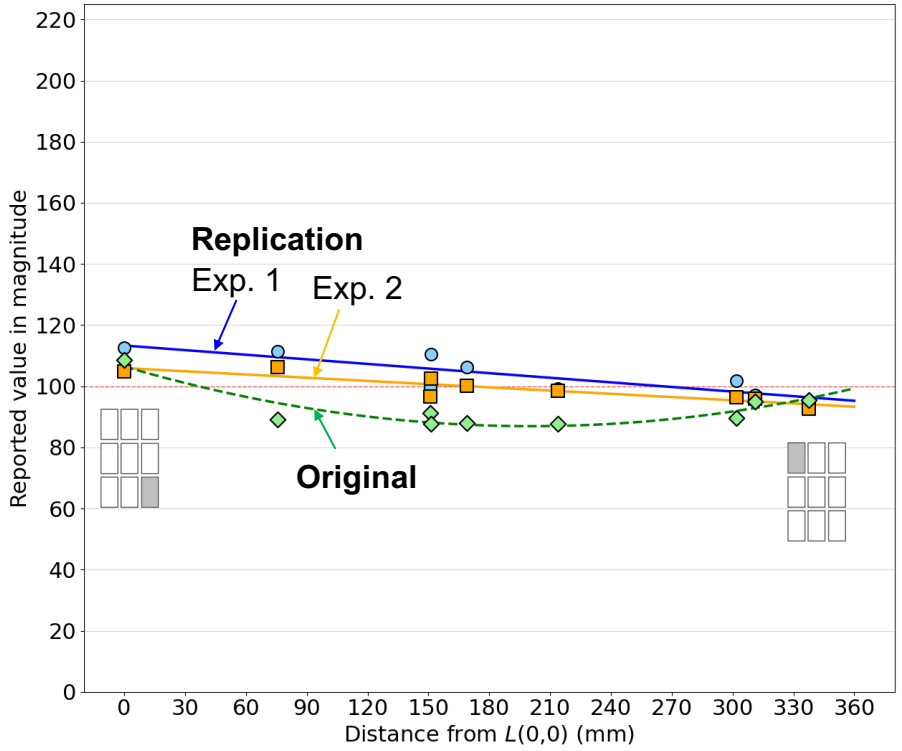


Matching grip did not restore the original delay pattern

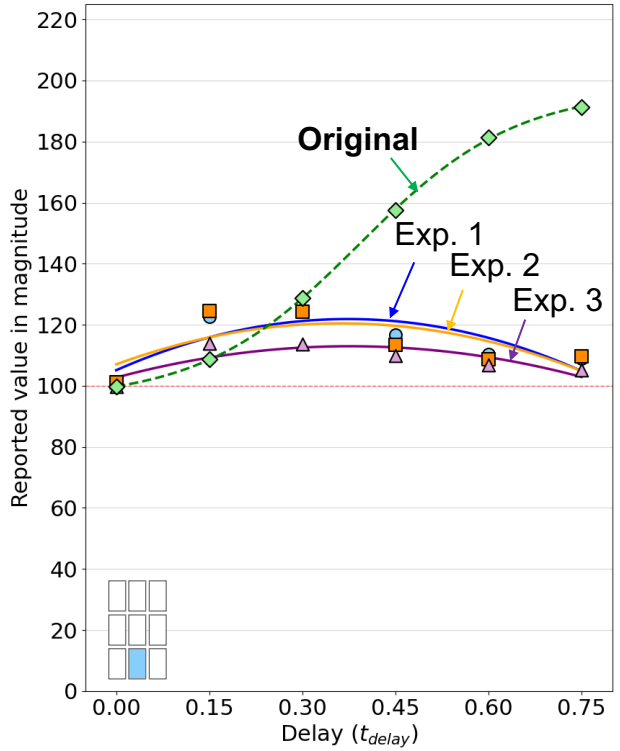
Results Across Experiments

- The non-monotonic delay response persisted across all three configurations.
- Device weight and grip style alone did not explain the difference from the original study.

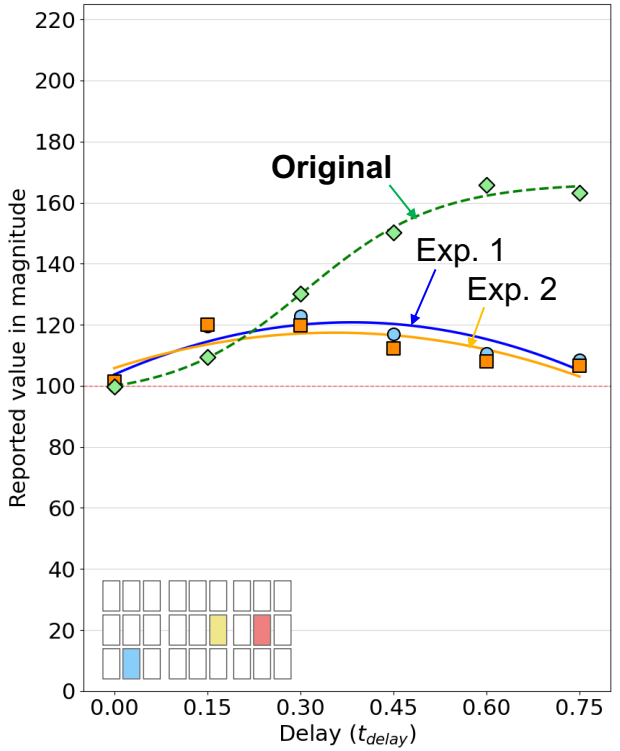
Layout



Delay (horizontal)



Delay (all)



Discussion

- Moderate delays may increase heaviness; longer delays may weaken device–window coupling.
  - Participants reported separation or loss of connection.
- Prior work reports saturation of delay-induced heaviness around **0.4 s** [1][2].
- Differences in baseline latency and participant samples may contribute to the discrepancy.
  - Camera latency: ≈ 0.30 s (original) vs. ≈ 0.05 s (replication).
  - Delay analysis: *N* = 8 (original) vs. *N* = 22 (replication).

[1] T. Honda et al., " Imposed visual feedback delay of an action changes mass perception based on the sensory prediction error." Front. Psychol., Vol. 4, No. 760, pp. 1-6, 2013.
[2] M. Kagami et al., "Tag-Along Virtual Windows Increase Perceived Resistance and Task Load in Augmented Reality," TVCG, Vol. 32, No. 5, pp. 4344-4353, 2026.

Summary

- Findings
  - Farther virtual displays made the handheld device feel lighter.
  - Weight ratings peaked around 0.30 s of delay and decreased at longer delays.
  - Neither matching mass nor matching grip restored the original monotonic trend.

- Future Work
  - Isolate the effect of baseline latency.
  - Examine how sense of agency relates to perceived weight.

Project Page