

Exploring Above-Neck Unimanual Swipe Gestures for Off-Device Earable Interaction

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Earables: Ear-mounted wearable devices

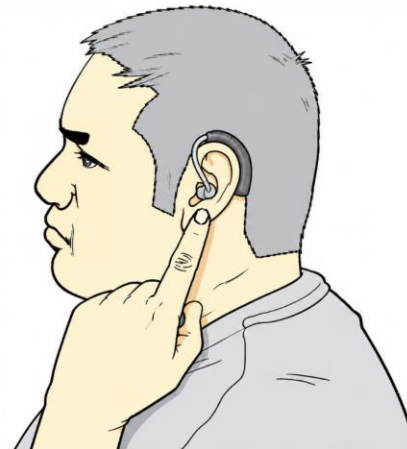
Great platforms for both hearing and head-based sensing.



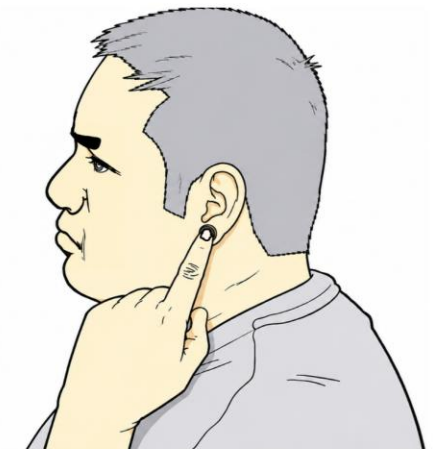
In-Ear Earable:
Apple AirPods



Over-Ear Earable:
Over-ear Headphones



Behind-Ear Earable:
Open-fit Hearing Aids



Lobule-Mounted Earable:
Ear-stud Electronic Accessories

Earables: Ear-mounted wearable devices

Most popular Earable Format?

- In-ear Earables
- Example: Apple Airpod



Small Form Factor, Limited On-Device
Space For Physical Interaction

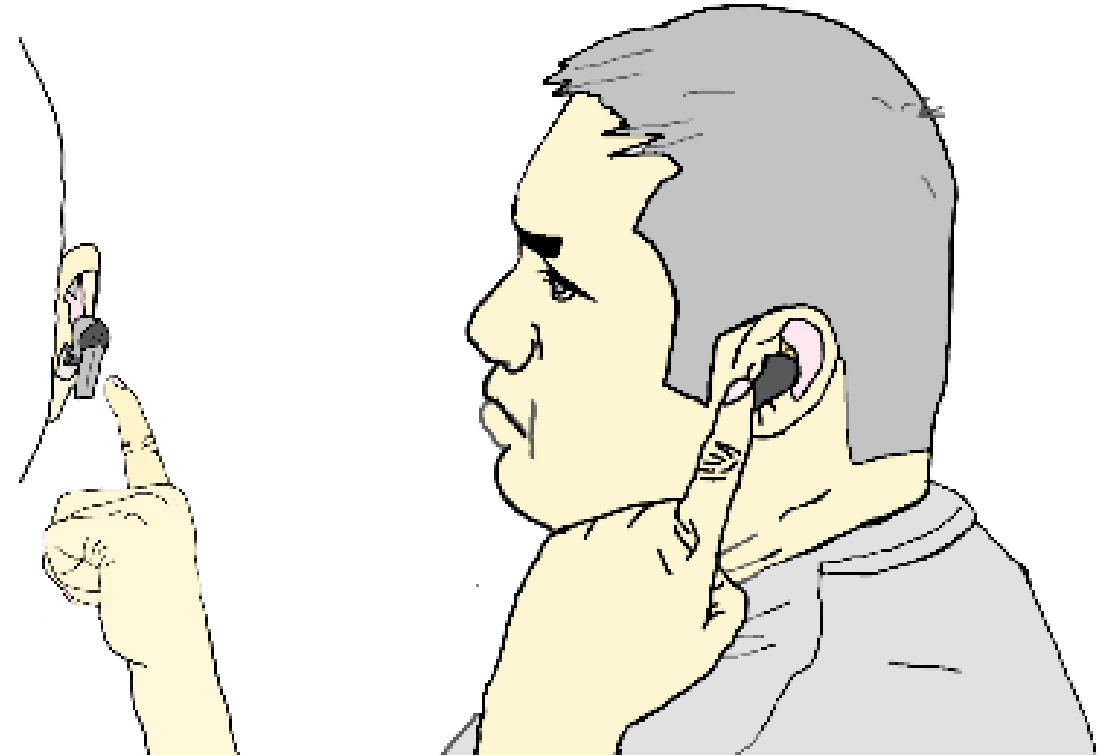
In-Ear Earables: Limited Physical Input Space

- **Solution:**

- Off-device inputs

- **Possible modalities**

- Head motion
 - Full-body motion
 - Facial expressions
 - Silent speech commands
 - **Hand-to-face gestures**



Unimanual, Non-Dominant Hand-Based Earable Interaction

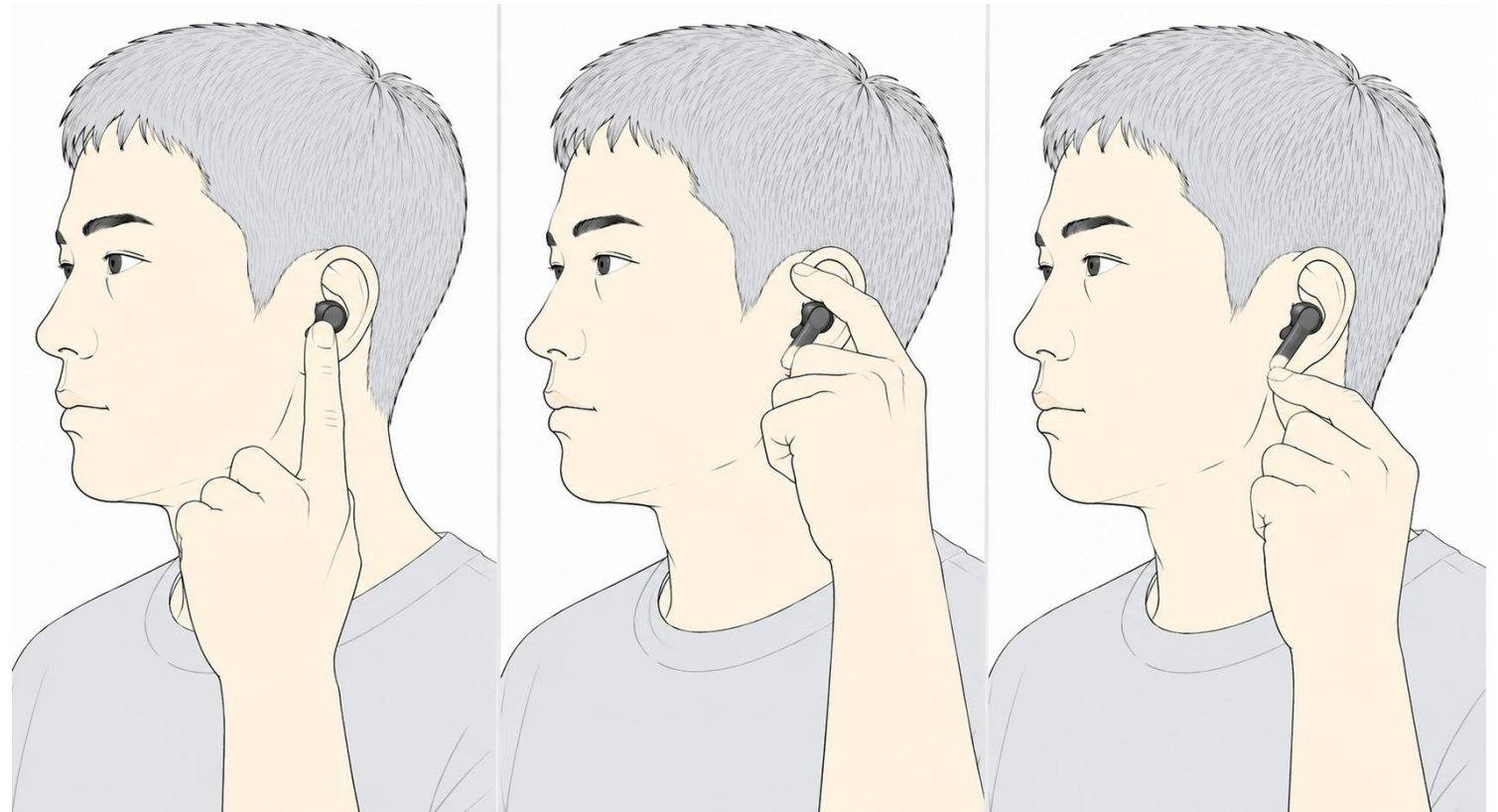
- Non-dominant hand (e.g., left hand for right-handed person) for interacting with ear-mounted wearable
- Dominant hand for simultaneously performing other tasks
 - Grabbing and interacting with mobile device
 - Hold and carry bag
 - Write using a pen



Roadblocks for Above-neck, Manual Earable Interaction?

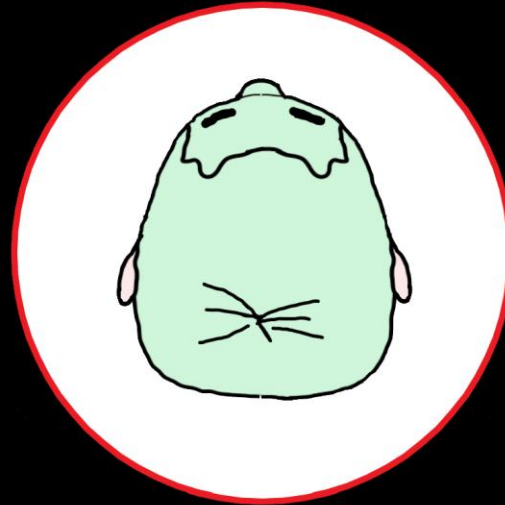
- **Problem**

- Touching the outer ear can displace in-ear earables

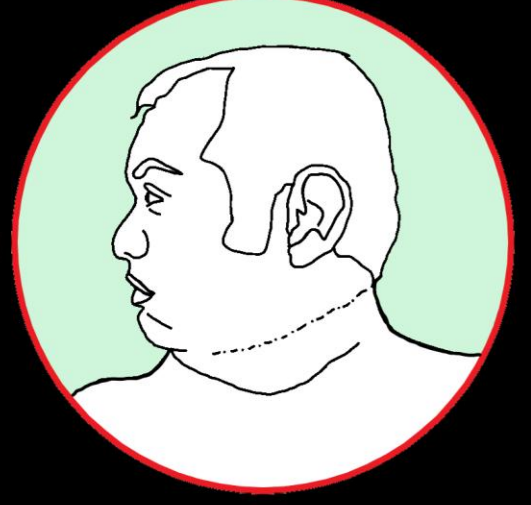
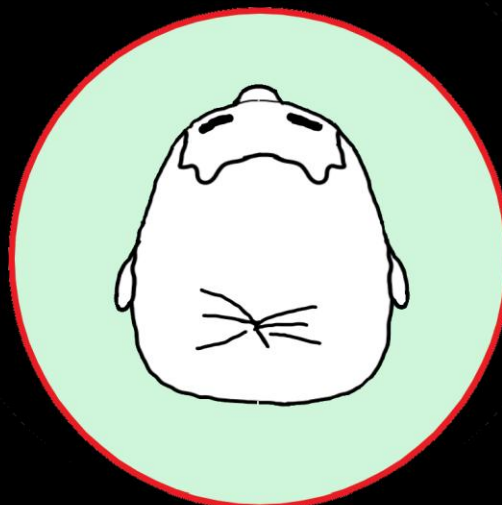


VIABLE INTERACTION SPACE FOR ABOVE-NECK EARABLE INTERACTION?

Avoid physical touch
with outer ear or
ear-mounted wearable



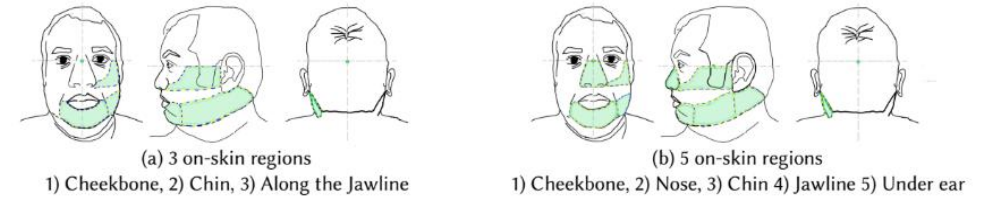
**Onskin space: Physical area on neck, face and head
except outer ear.**



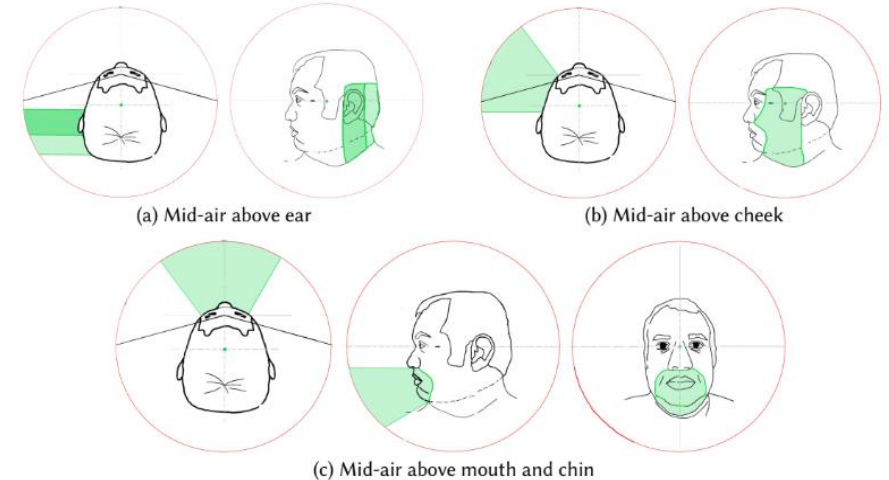
Midair space: Above neck and around face and ears

Expanding Off-Device Vocabulary Using Above-Neck Gestures

- Prior work explored unimanual input bounded within specific around-ear regions
- Works for taps / pinches
- Swipes don't scale well with small, bounded regions



Suggested On-Skin Regions



Suggested Mid-Air Regions

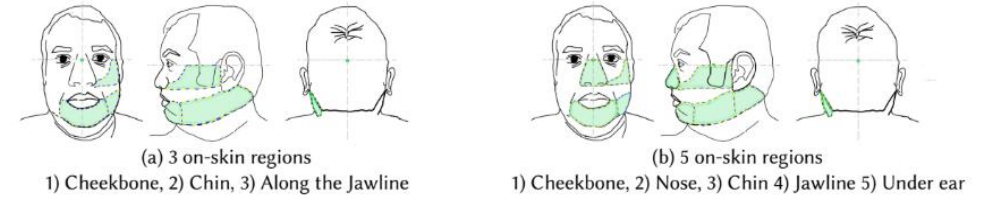
Small region boundaries suggested in location-based gesture reuse (prior research)

Expanding Off-Device Vocabulary Using Above-Neck Gestures

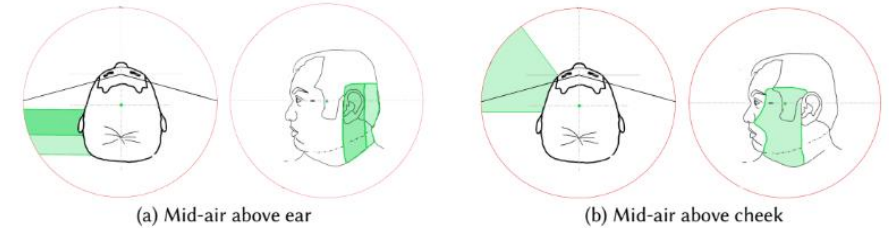
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Tap

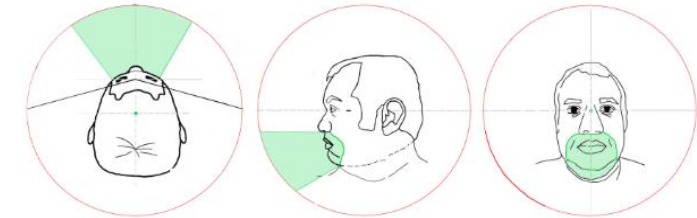


Suggested On-Skin Regions



(a) Mid-air above ear

(b) Mid-air above cheek



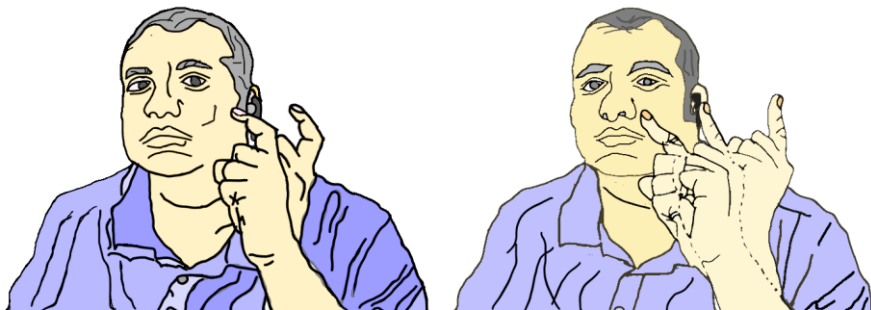
(c) Mid-air above mouth and chin

Suggested Mid-Air Regions

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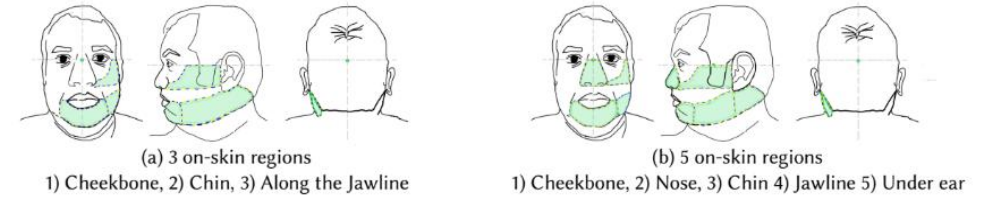
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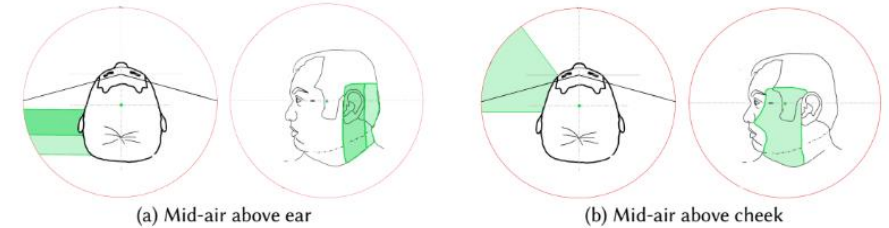


Tap

Swipe



Suggested On-Skin Regions

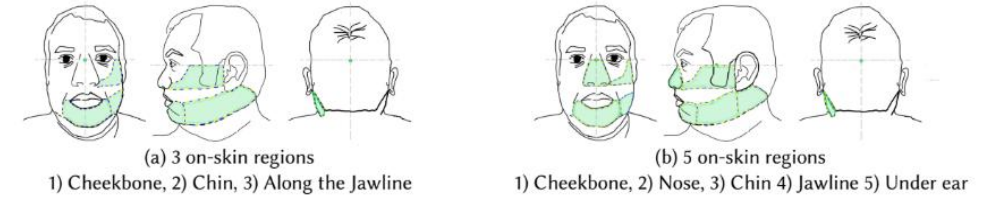
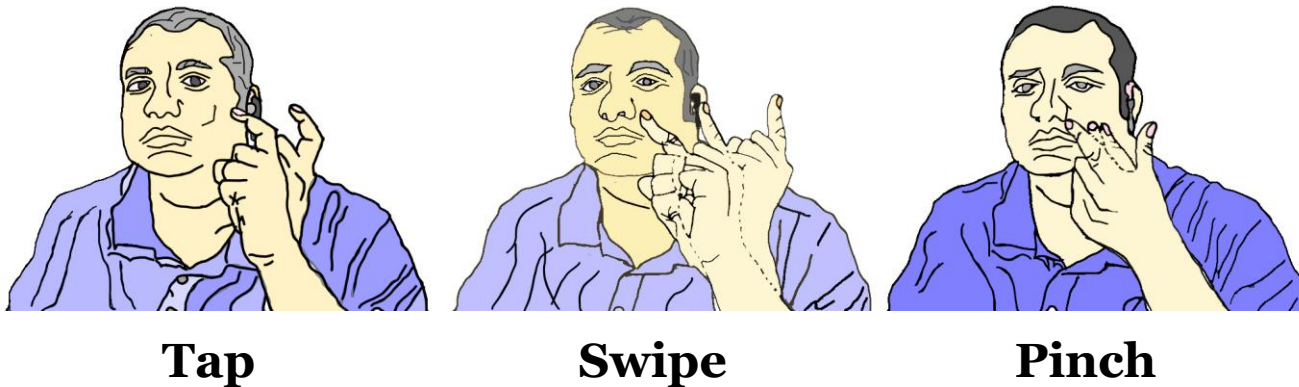


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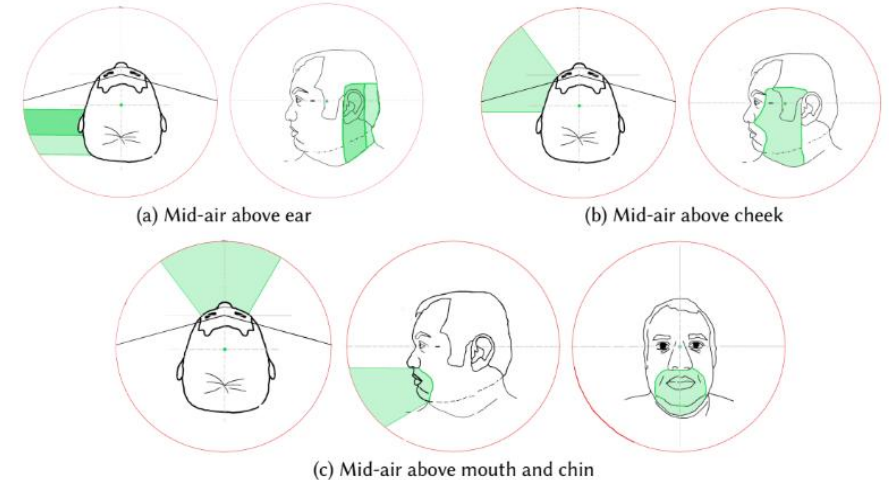
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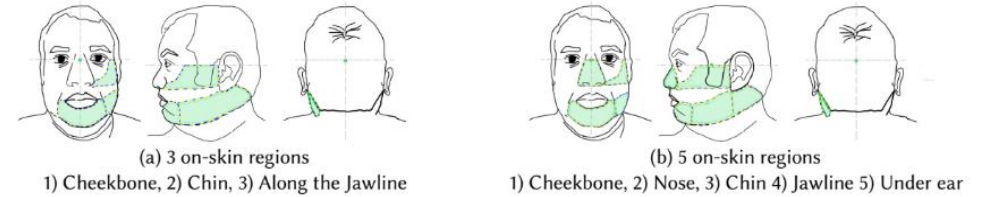
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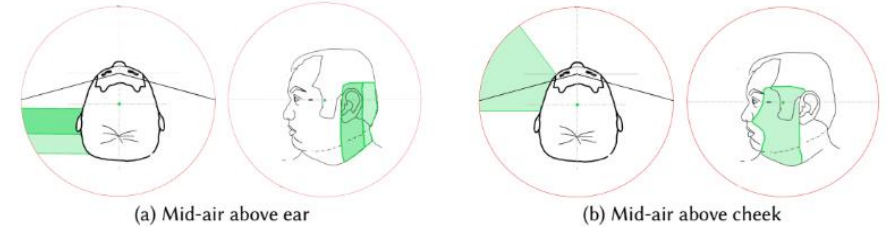
Tap



Pinch

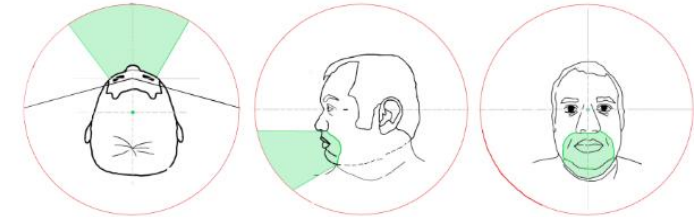


Suggested On-Skin Regions



(a) Mid-air above ear

(b) Mid-air above cheek



(c) Mid-air above mouth and chin

Suggested Mid-Air Regions

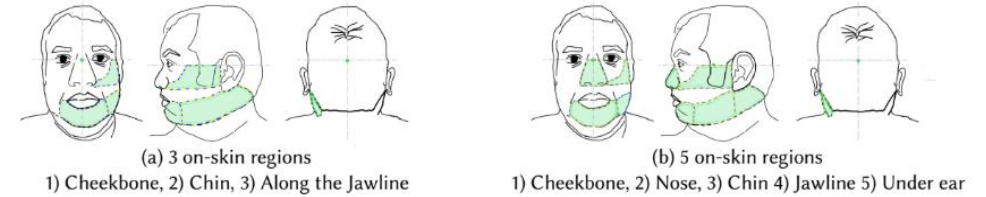
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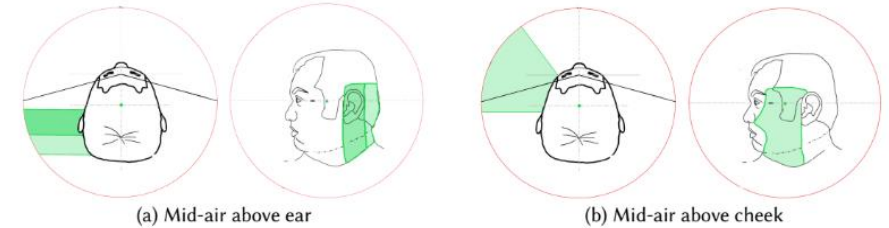
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Swipe

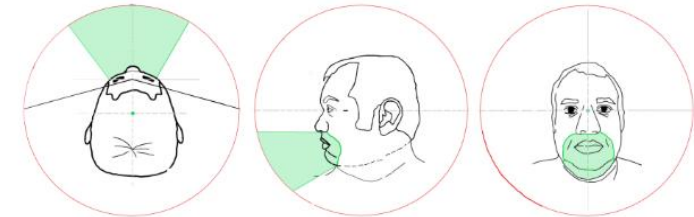


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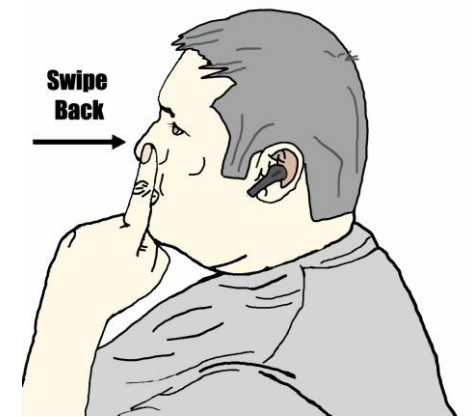
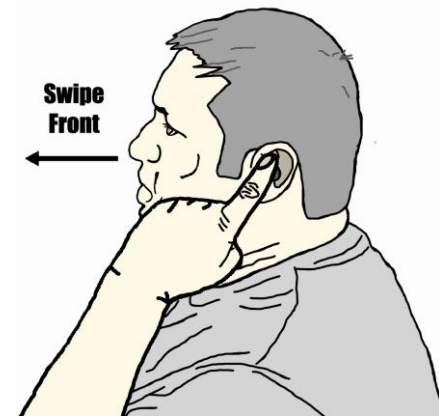
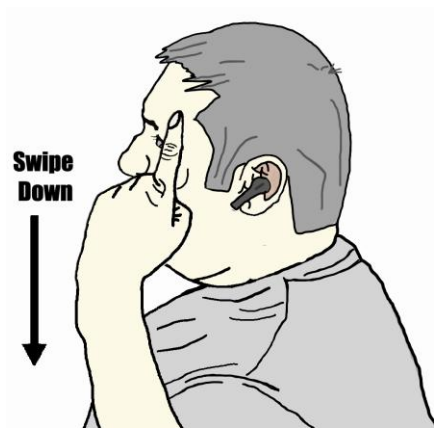
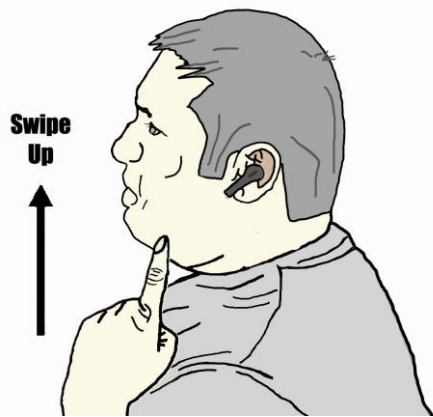
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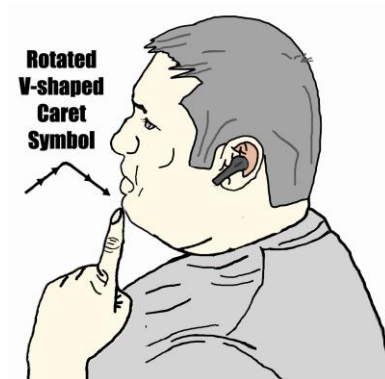
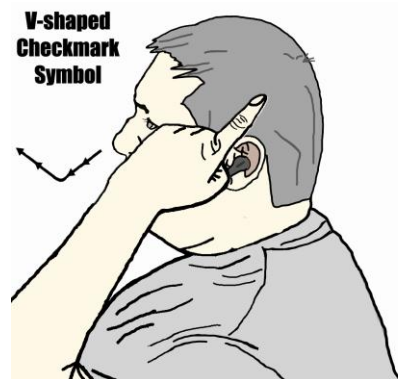
Expanding Off-Device Vocabulary Using Above-Neck Gestures

- Assumption in prior work
 - Ear-adjacent swipes are treated as **axial gestures** (horizontal / vertical)



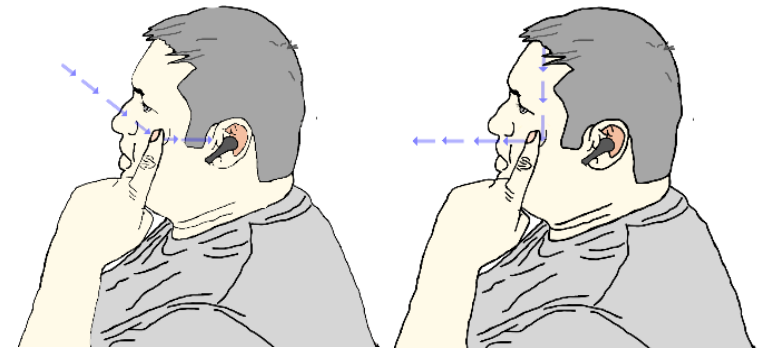
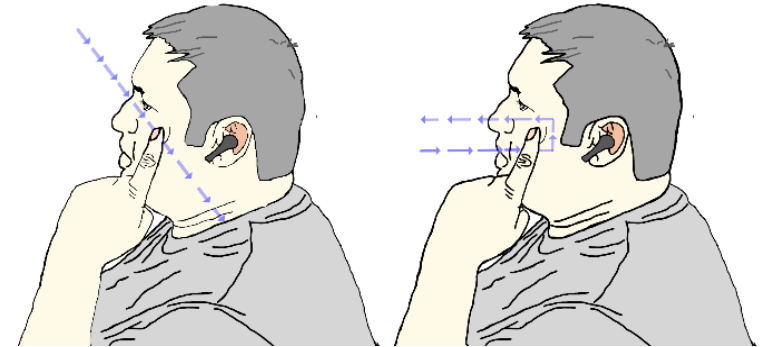
Unimanual Off-Device Earable Swipe: Research Gaps

- **But elicitation studies reveal**
 - Users naturally produce **non-axial and angular gestures** (*L, U, V shapes*)
- **And gesture research shows**
 - Shapes like **✓ checkmarks** and **^ carets** convey semantic meaning (*confirmation, selection*)



Why Unidirectional (Axial/Non-Axial) & Angular Swipes?

- Prior research favors unistroke gestures
 - Low shape complexity
 - Easy to recall and execute

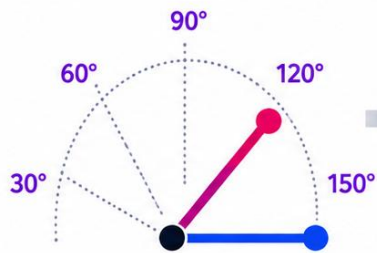


1 Two swipe segments



A shape is formed by joining two swipe segments.

2 Different angles



Segments can be joined at different angles.

3 Variations by orientation

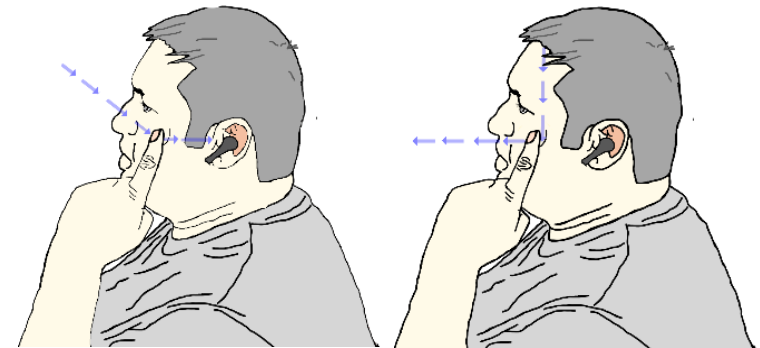
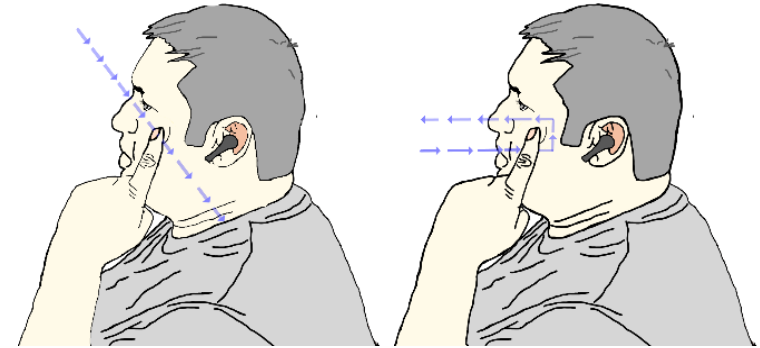


Changing orientations creates a variety of unistroke swipe shapes.

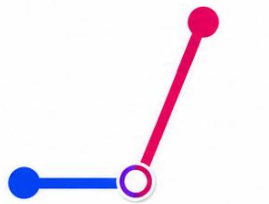
Variation of non-axial and angular swipes

Creating Unistroke Above-neck, Unidirectional / Angular Swipes

- Unistroke shapes like \checkmark checkmarks and \wedge carets can be formed by
 - joining **two swipe segments** at **different angles**, and
 - **varying their orientations**

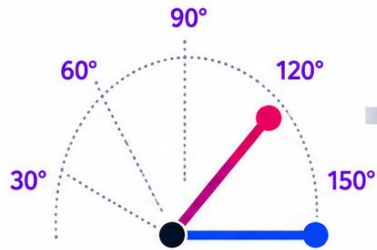


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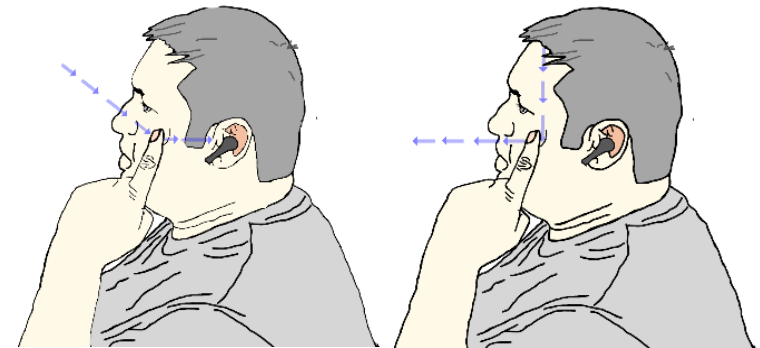
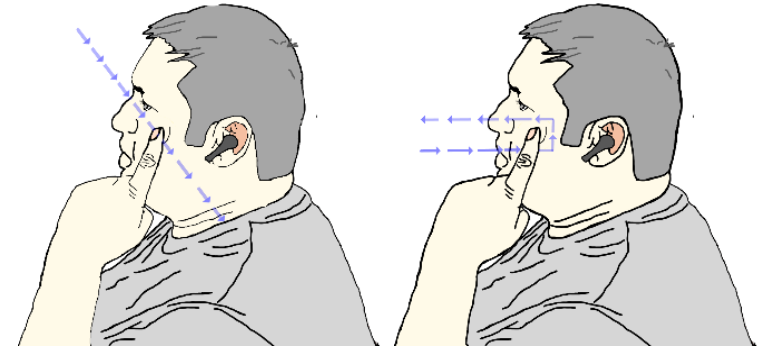
Changing **orientations** creates a variety of unistroke swipe shapes.

Variation of non-axial and angular swipes

Expanding Off-Earable Input Vocabulary Using Swipe Variation



Swipe originates in starting region (**Green**), changes direction over a facial landmark (**Yellow**), and terminates at a ending region (**Blue**)

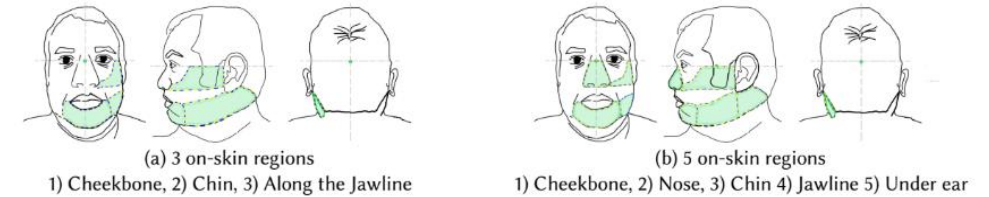


Variation of non-axial and angular swipes

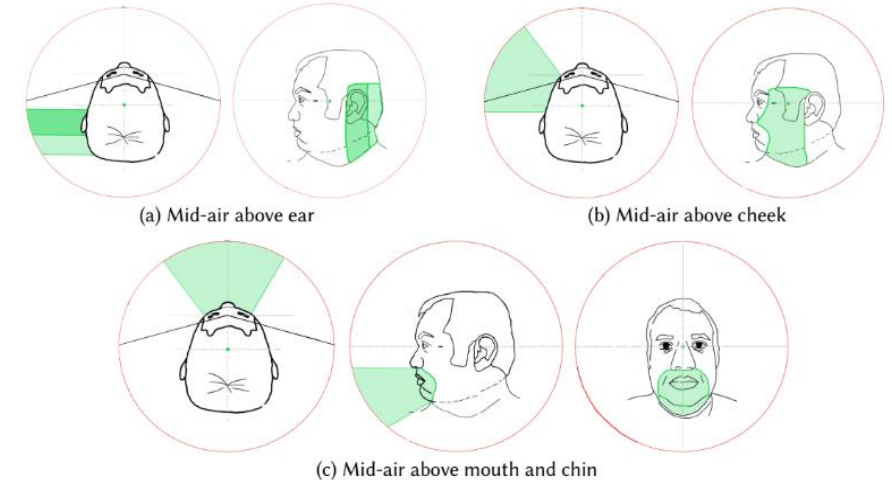
Expanding Off-Earable Input Vocabulary Using Swipe Variation



Using unistroke swipes that change directions on or above a focal point, we avoid precision issues with small region boundaries suggested in location-based gesture reuse (prior work)



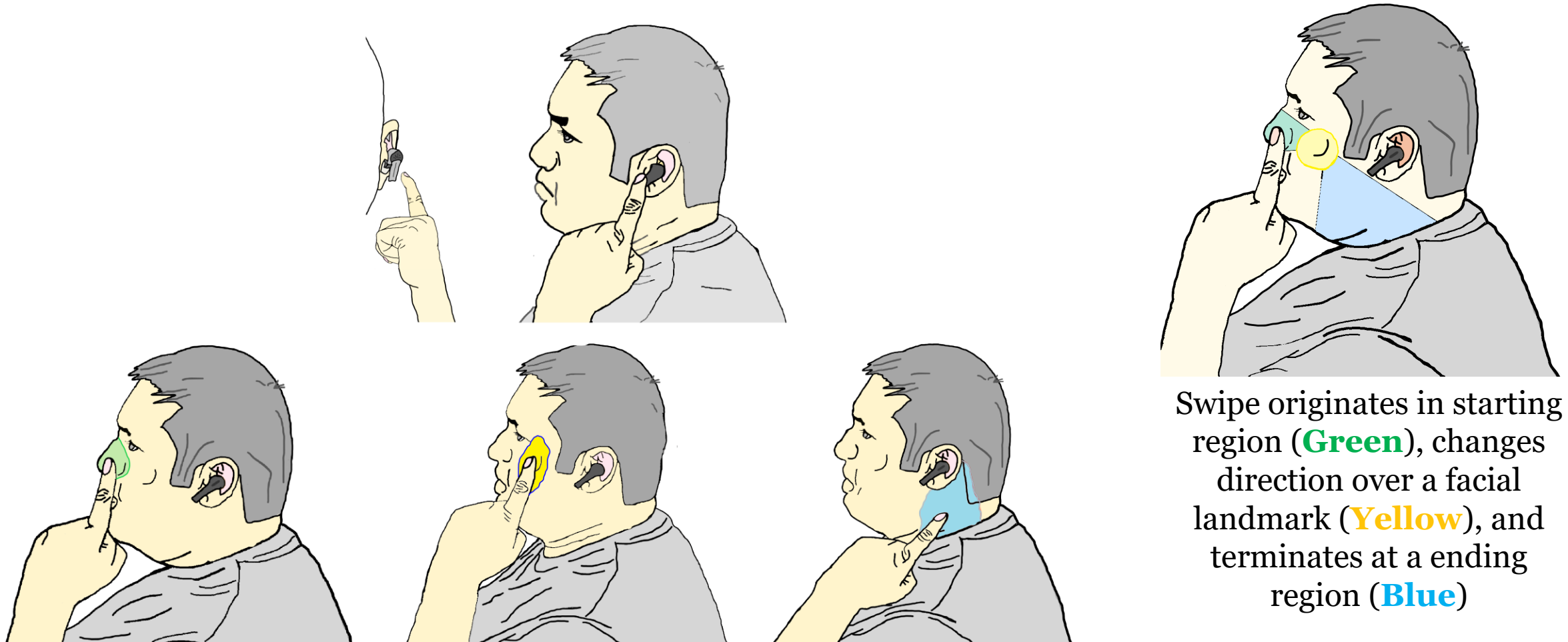
Suggested On-Skin Regions



Suggested Mid-Air Regions

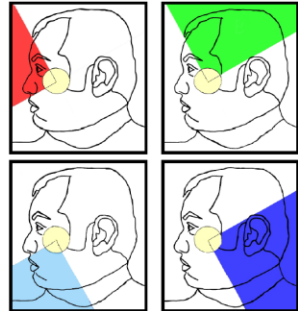
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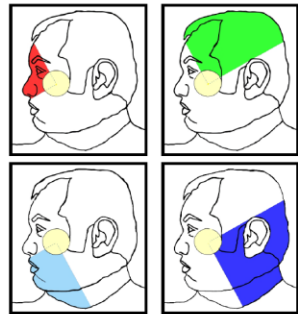
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Expanding Off-Earable Input Vocabulary Using Swipe Variation



A B C D

(a) 4 Midair



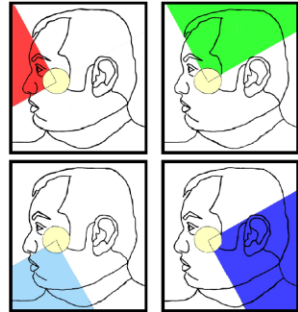
A B C D

(d) 4 Onskin



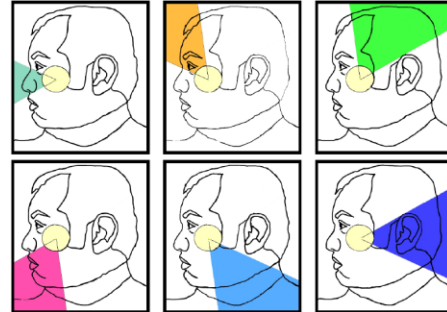
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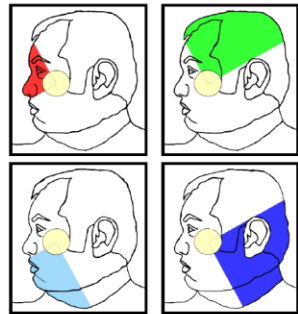
A B C D

(a) 4 Midair



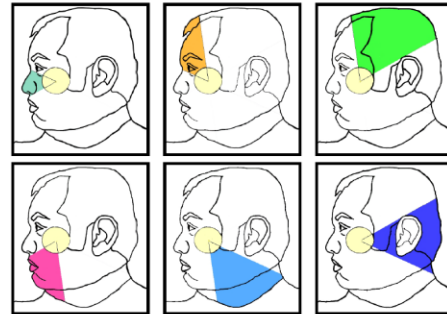
A B C D E F

(b) 6 Midair



A B C D

(d) 4 Onskin



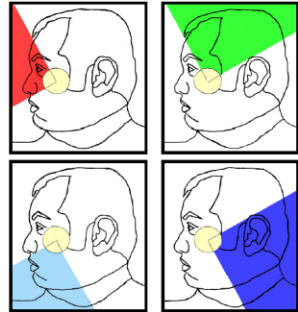
A B C D E F

(e) 6 Onskin



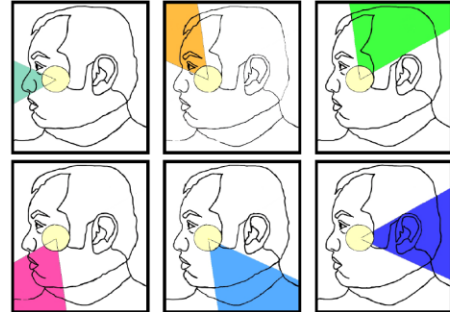
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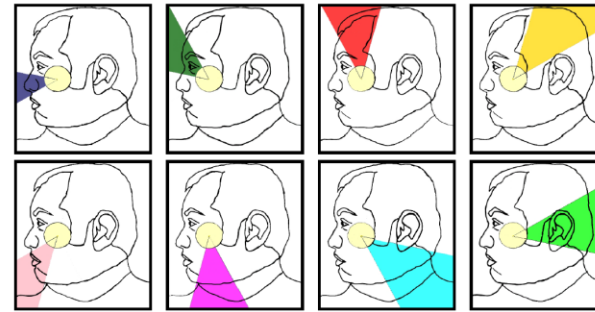
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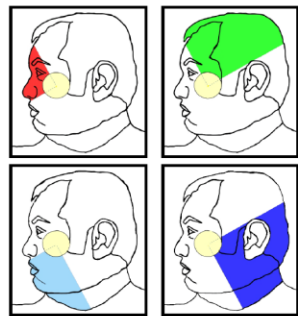
A B C D E F

(b) 6 Midair



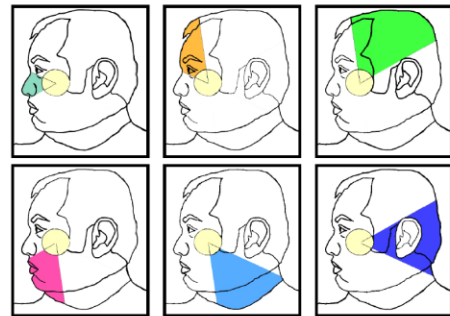
A B C D E F G H

(c) 8 Midair



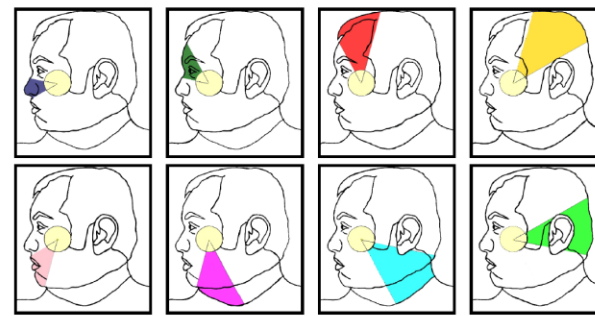
A B C D

(d) 4 Onskin



A B C D E F

(e) 6 Onskin



A B C D E F G H

(f) 8 Onskin



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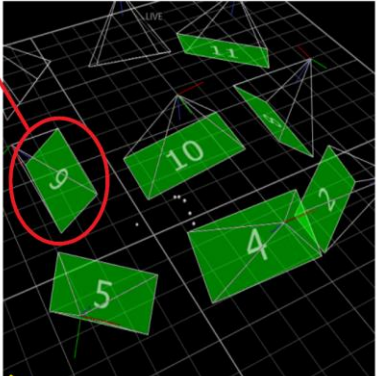
4, 6 and 8-region segmentation centered on (onskin) / above (midair) cheekbone as the swipe focal point (marked in **Yellow**)

Imaginary Interface Approach: Swipe Motion Analysis Using Vicon



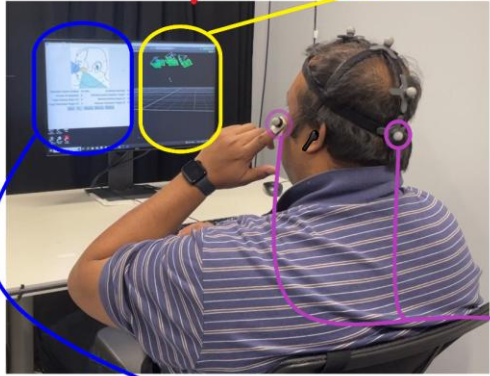
Vicon Camera on ceiling

Vicon Workstation



Finger & Head Markers showing on Vicon Tracker 3.9 Application with respect to Vicon Cameras

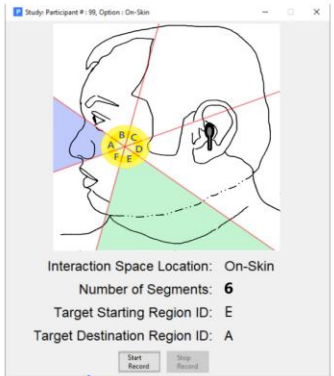
Vicon Tracker 3.9 Application shown on Workstation Monitor



Earbud

Marker

Gesture Task Shown on Workstation Monitor



Gesture Task prompt showing swipe starting region in green, ending region in light blue, and swipe direction change region on cheekbone

Experimental Design & Participants

- **Independent Variables**

- **Interaction Space (2)**

- Midair | On-skin

- **Region Density (3)**

- 4 regions | 6 regions | 8 regions

- **Study Structure**

- 2 Spaces × 3 Region Densities
= 6 Gesture Blocks

- **Swipe Conditions**

- **116** possible swipes per interaction space

- **Participants (24 = 15 M, 9 F)**

- $\mu = 29.33$ year, **SD** = 7.20

- **None with hand, arm or finger joint issues**

- **Study Length**

- 90 min session X 2 day
 - Each day for a specific interaction space

- **Gesture Collected**

- 5568 swipes
 - 1 Trial / participant

Research Questions

- **RQ1 — Interaction Space**

How do **swipe performance** and **workload** differ between **midair** and **on-skin interaction**?

Research Questions

- **RQ1 — Interaction Space**

How do **swipe performance** and **workload** differ between **midair** and **on-skin interaction**?

- **RQ2 — Region Density**

How does increasing the **number of gesture regions** affect **swipe performance** and **workload**?

Research Questions

- **RQ1 — Interaction Space**

How do **swipe performance** and **workload** differ between **midair and on-skin interaction**?

- **RQ2 — Region Density**

How does increasing the **number of gesture regions** affect **swipe performance** and **workload**?

- **RQ3 — Region Location**

Within a fixed interaction setup, how do **start/end region locations** affect **performance** and **region preference**?

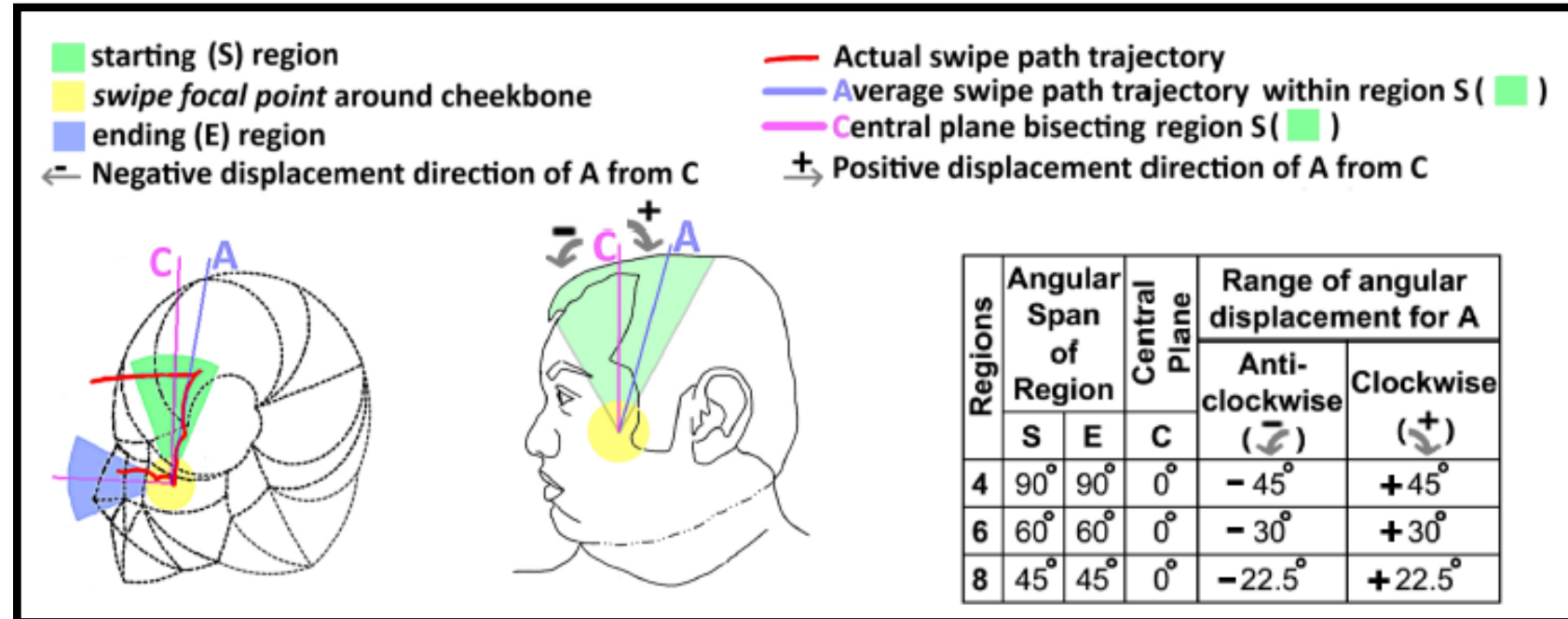
Evaluation Metrics

- **Performance**

- Accuracy (DV1)
- Time (DV2)
- Path Length (DV3)
- Angular Drift (DV4)

- **User Experience**

- NASA-TLX
- Region Rating
 - Swipe starting position
 - Swipe ending position

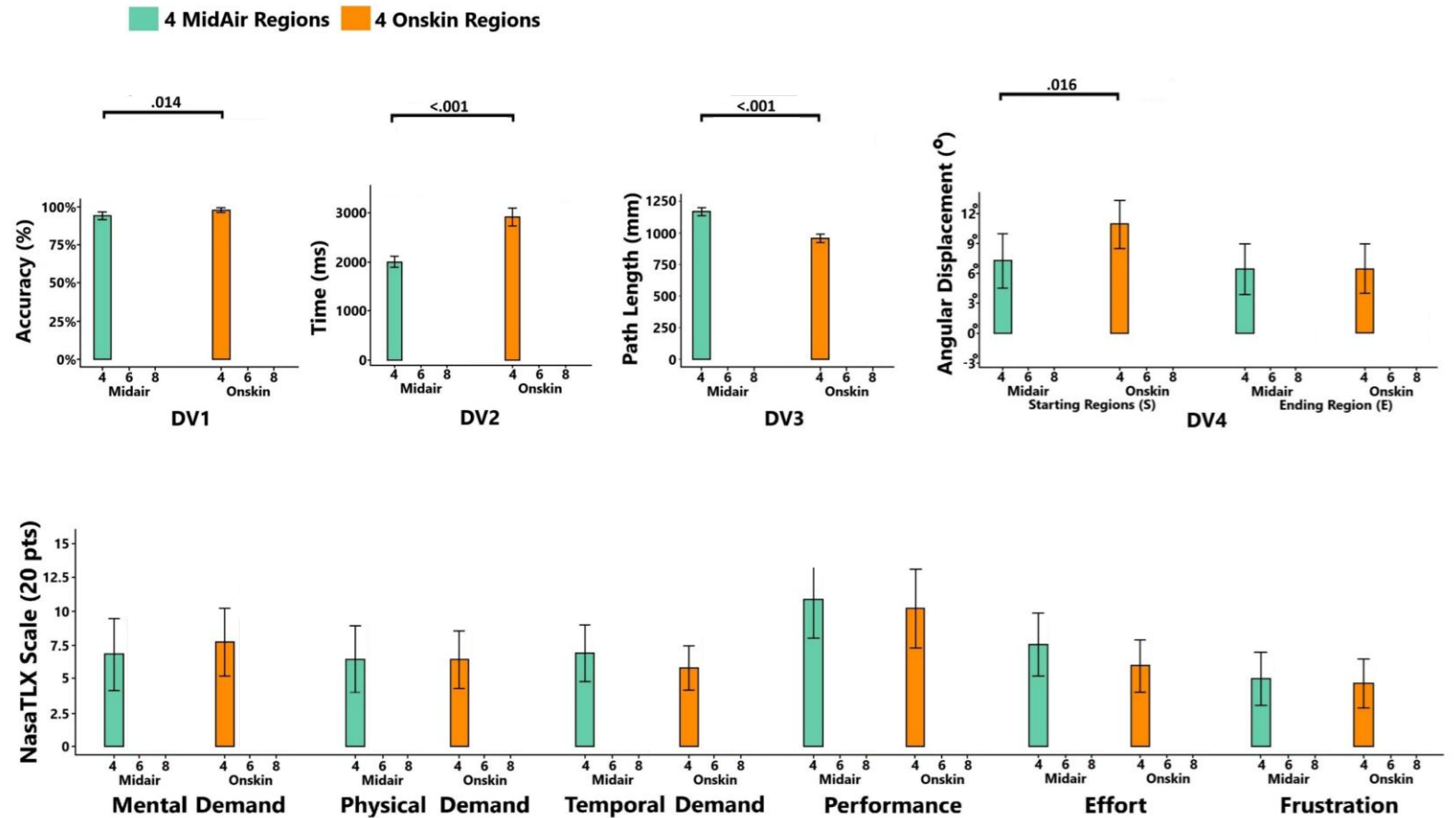


Angular drift of swipe segment (red line) in the starting region (Green region) with respect to line C, the central plane for starting region. Line A is the average trajectory of the swipe segment within starting Region. **Angular drift = angle between A and C.**

RQ1 & RQ2 Results:

Onskin Better at 4 Regions, Midair Better at ≥ 6 Regions

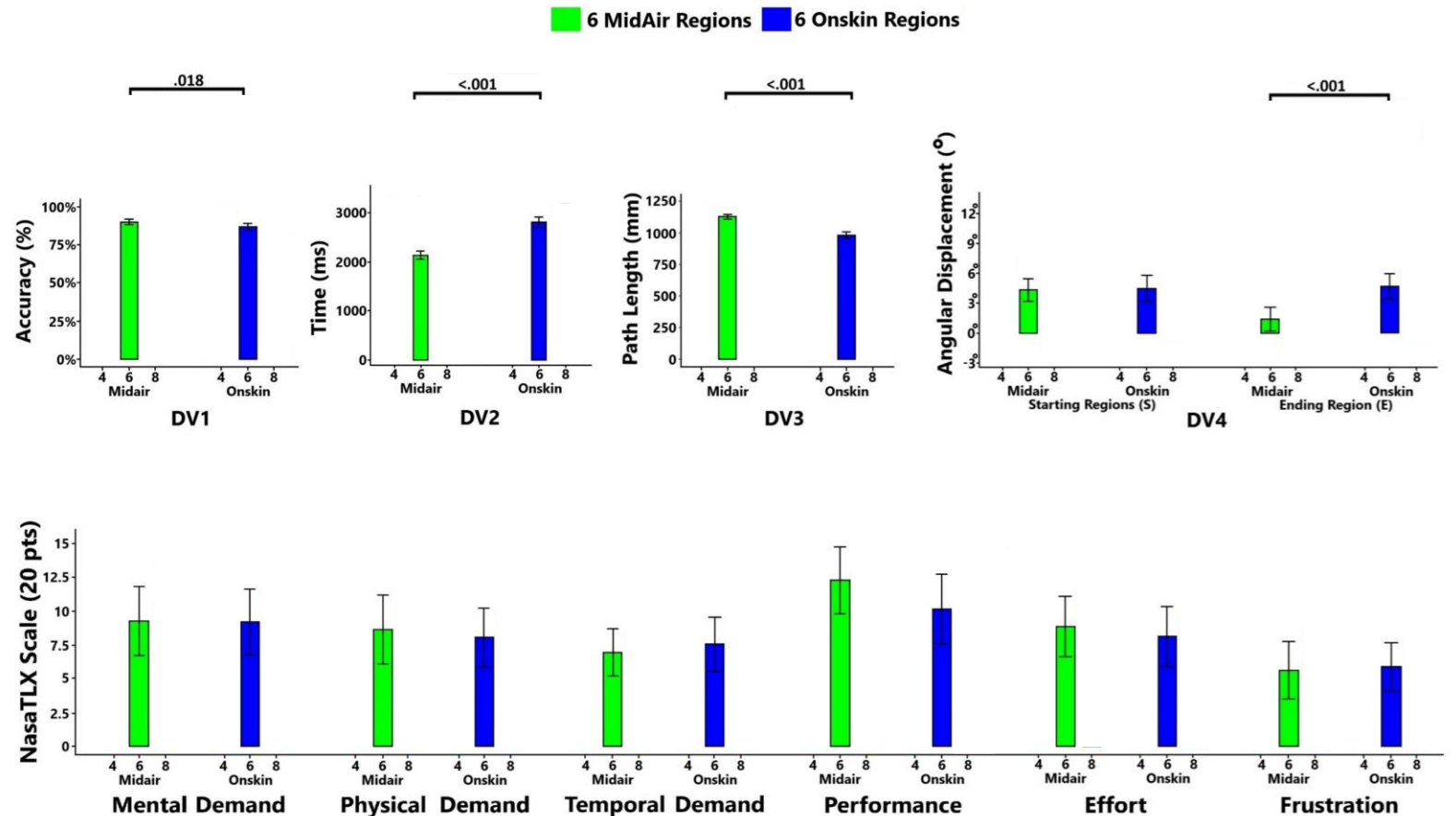
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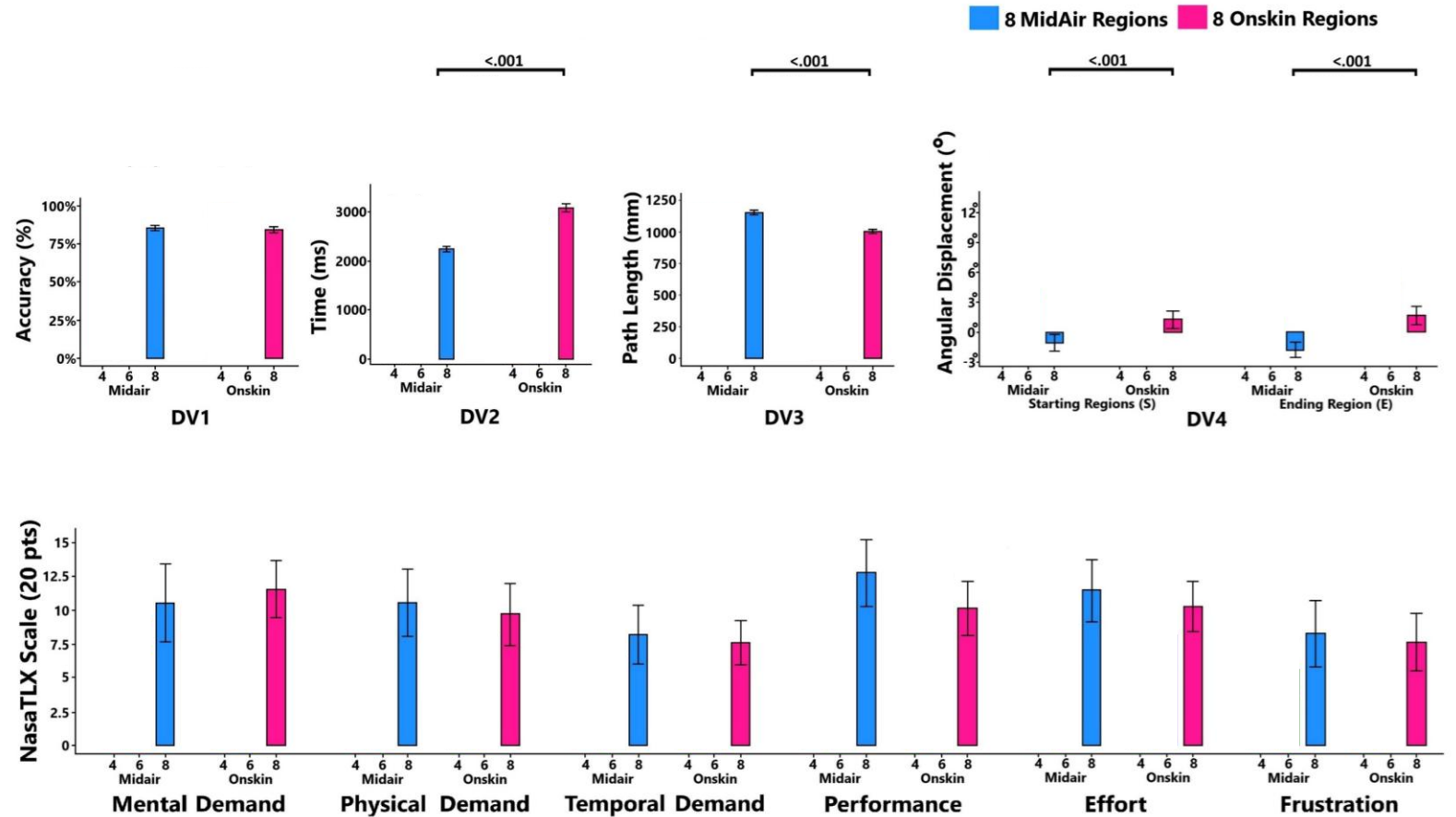
- On-skin swipes favored 4 regions
- Higher densities (> 4) increased constraints and placement sensitivity for on-skin swipes.
- Midair swipes favored ≥ 6 regions.



RQ1 & RQ2 Results:

Onskin Better at 4 Regions, Midair Better at ≥ 6 Regions

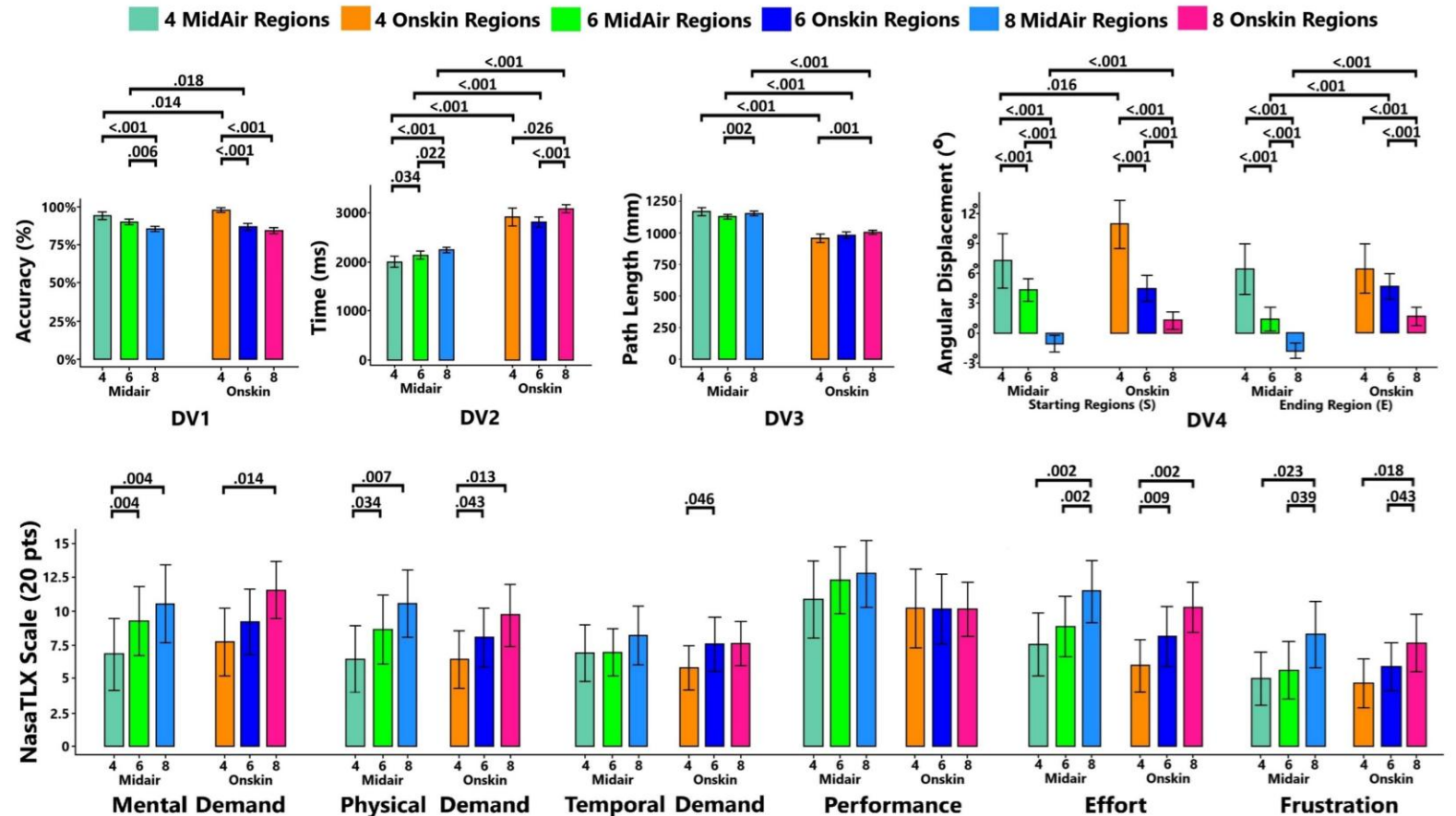
- On-skin swipes favored 4 regions
- Higher densities (> 4) increased constraints and placement sensitivity for on-skin swipes.
- Midair swipes favored ≥ 6 regions.



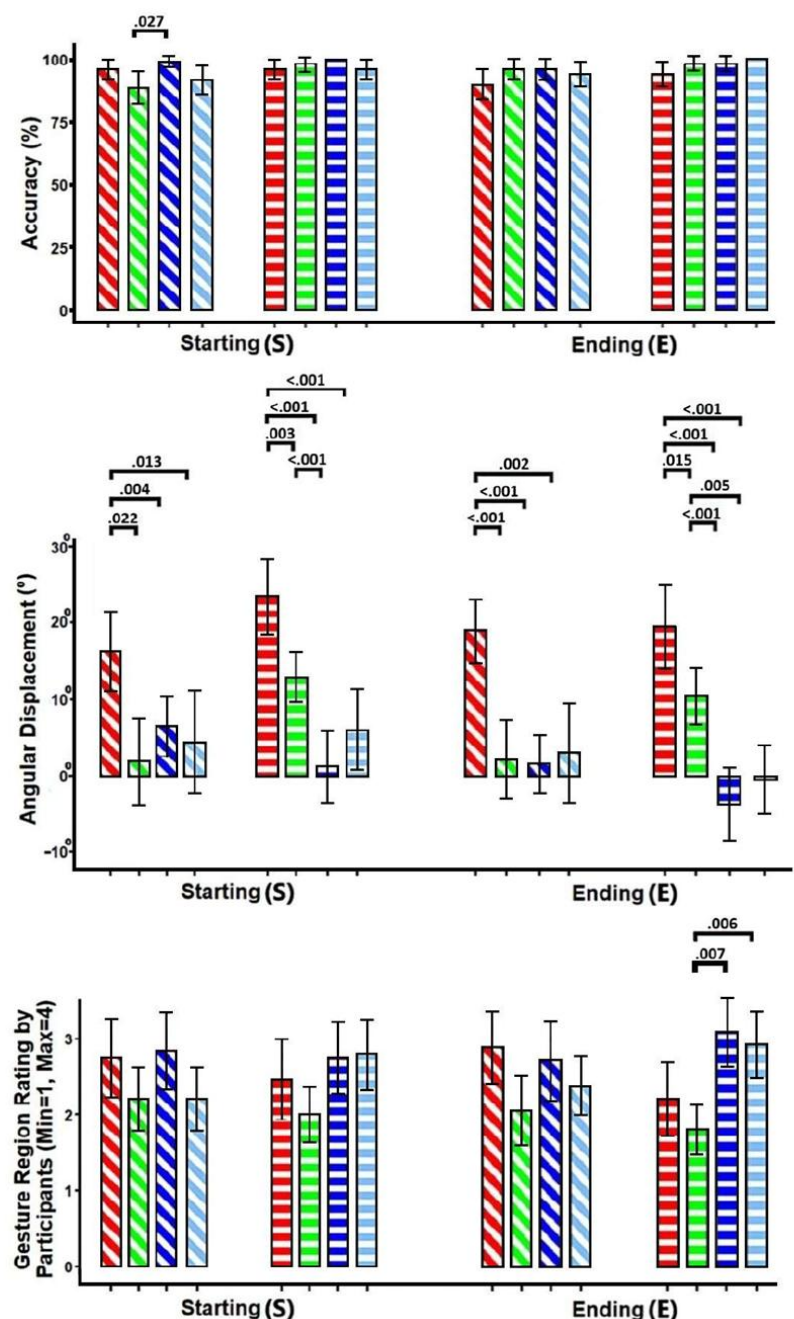
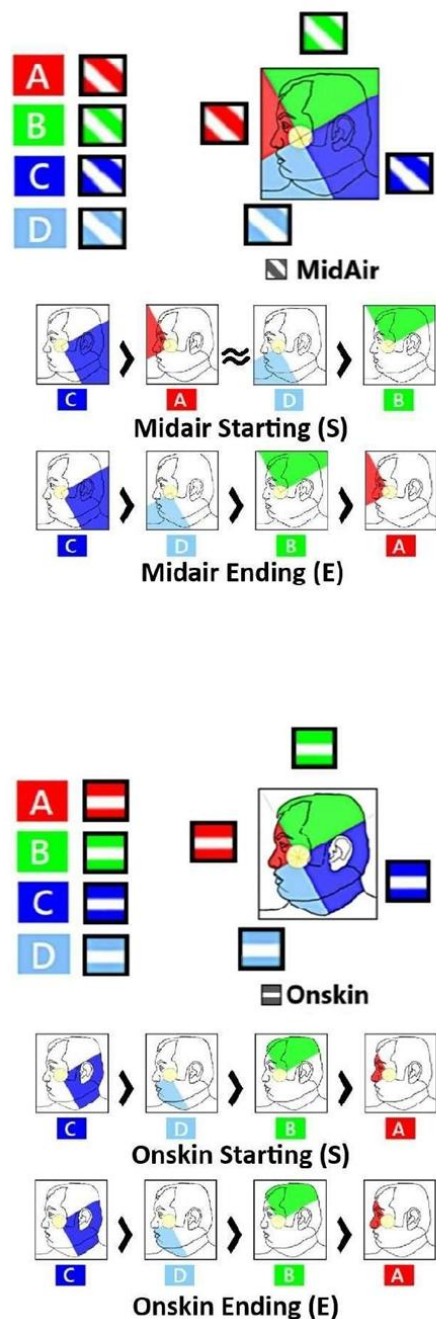
RQ1 & RQ2 Results:

Optimum Segmentation ≤ 6 Regions For Both Spaces

- On-skin swipes favored 4 regions
- midair swipes favored ≥ 6 regions.
- Higher densities (> 4) increased constraints and placement sensitivity for on-skin swipes.
- Performance degraded markedly at 8 regions in both interaction spaces.



RQ3 Results: 4 Region Layout



RQ3 Results: 4 Midair Pattern

Ear (C), Followed by Nose (A) Are Best Swipe Starting Positions

$$C > A \approx D > B$$



C: ↑Accuracy, ↓Displacement;
 A: ↑displacement; good accuracy and ratings; within visual range

Figure : Relative performance of 4 swipe regions across interaction spaces. Arrows indicate metric trends contributing to the ranking (Accuracy / Ranking ↑ higher & Displacement ↓ lower is better). Accuracy = DV1, Angular Displacement = DV4, Ratings = Subjective swipe region ratings.

4 Region Segmentation			
Unidirectional		Angular	
Axial		U-Shaped (180°)	L-Shaped (90°)

Swipe Group	Stable	Moderate	Unstable	Observation
Axial	AC, BD DB	CA	-	Axial swipes show high stability.
U-shaped (180°)	BB, CC DD	AA	-	Loops reliable near ear, temple and chin.
L-shaped (90°)	CB	BC, DC CD	AB, AD BA, DA	Angular swipes show higher variability; especially when terminating around eye.

(a) Midair

Figure : Swipe shape stability under 4-region segmentation derived from accuracy (DV1), angular displacement (DV4), and subjective ratings.

RQ3 Results: 4 Midair Pattern

Ear (C), Followed by Chin (D) Are Best Swipe Ending Positions

$$C > D > B > A$$

C / D: lowest displacement
A: highest displacement



Figure : Relative performance of 4 swipe regions across interaction spaces. Arrows indicate metric trends contributing to the ranking (Accuracy / Ranking ↑ higher & Displacement ↓ lower is better). Accuracy = DV1, Angular Displacement = DV4, Ratings = Subjective swipe region ratings.

4 Region Segmentation			
Unidirectional		Angular	
Axial		U-Shaped (180°)	L-Shaped (90°)

Swipe Group	Stable	Moderate	Unstable	Observation
Axial	AC, BD DB	CA	-	Axial swipes show high stability.
U-shaped (180°)	BB, CC DD	AA	-	Loops reliable near ear, temple and chin.
L-shaped (90°)	CB	BC, DC CD	AB, AD BA, DA	Angular swipes show higher variability; especially when terminating around eye.

(a) Midair

Figure : Swipe shape stability under 4-region segmentation derived from accuracy (DV1), angular displacement (DV4), and subjective ratings.

RQ3 Results: 4 Onskin Pattern

Ear (C), Followed by Chin (D) Are Best Swipe Starting Positions

$$C > D > B > A$$

C / D: ↓Displacement; C / D: ↑Ratings

A: low rating, accuracy, high displacement



Figure : Relative performance of 4 swipe regions across interaction spaces. Arrows indicate metric trends contributing to the ranking (Accuracy / Ranking ↑ higher & Displacement ↓ lower is better). Accuracy = DV1, Angular Displacement = DV4, Ratings = Subjective swipe region ratings.

4 Region Segmentation			
Unidirectional		Angular	
Axial		U-Shaped (180°)	L-Shaped (90°)

Swipe Group	Stable	Moderate	Unstable	Observation
Axial	AC, CA BD, DB	-	-	Axial swipes show high stability.
U-shaped (180°)	BB, CC DD	AA	-	U-shaped Loops reliable near ear and chin Nose loop shows larger but manageable drift.
L-shaped (90°)	-	AD, DC, CD BC, CB	AB, BA DA	Angular swipes involving region A showed weakest stability.

(b) Onskin

Figure : Swipe shape stability under 4-region segmentation derived from accuracy (DV1), angular displacement (DV4), and subjective ratings.

RQ3 Results: 4 Onskin Pattern

Ear (C), Followed by Nose (A) Are Best Ending Positions

$$C > D > B > A$$

C / D: ↓Displacement; C / D: ↑Ratings

A: low rating, accuracy, high displacement



Figure : Relative performance of 4 swipe regions across interaction spaces. Arrows indicate metric trends contributing to the ranking (Accuracy / Ranking ↑ higher & Displacement ↓ lower is better). Accuracy = DV1, Angular Displacement = DV4, Ratings = Subjective swipe region ratings.

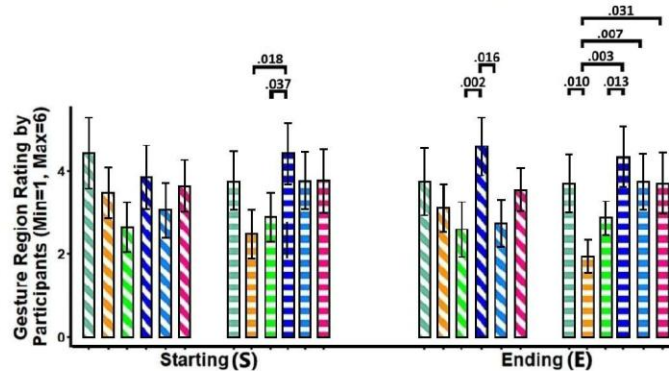
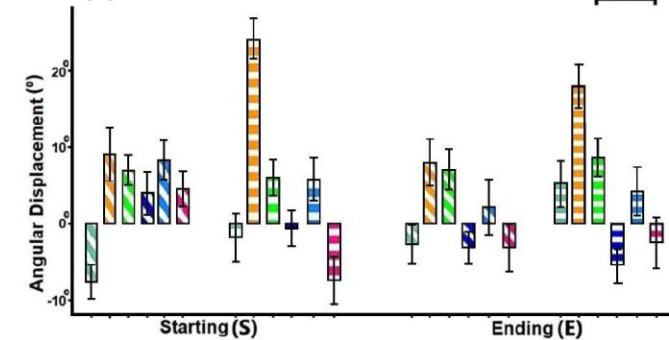
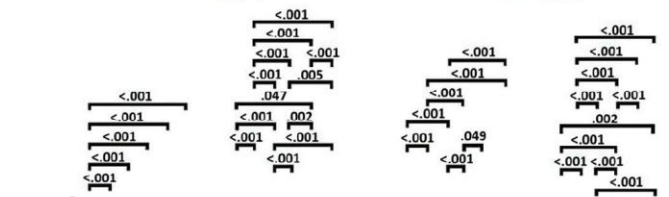
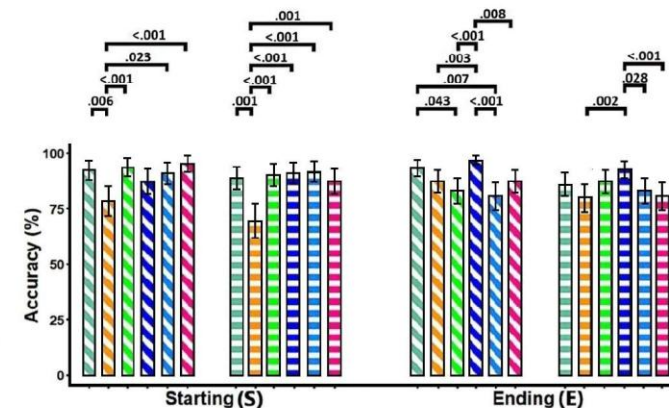
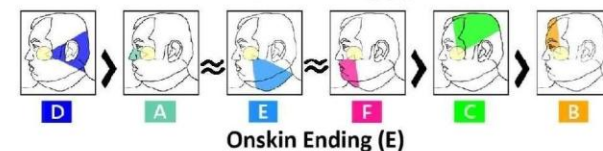
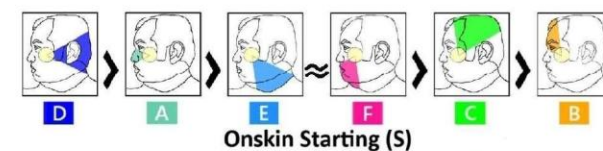
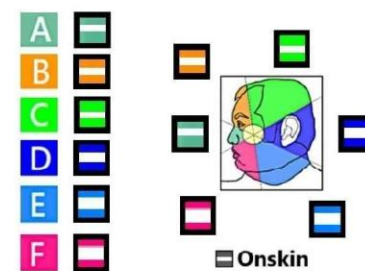
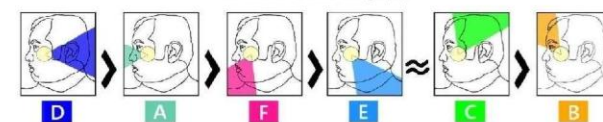
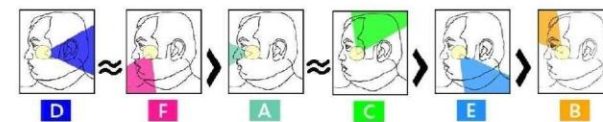
4 Region Segmentation			
Unidirectional		Angular	
Axial		U-Shaped (180°)	L-Shaped (90°)

Swipe Group	Stable	Moderate	Unstable	Observation
Axial	AC, CA BD, DB	-	-	Axial swipes show high stability.
U-shaped (180°)	BB, CC DD	AA	-	U-shaped Loops reliable near ear and chin Nose loop shows larger but manageable drift.
L-shaped (90°)	-	AD, DC, CD BC, CB	AB, BA DA	Angular swipes involving region A showed weakest stability.

(b) Onskin

Figure : Swipe shape stability under 4-region segmentation derived from accuracy (DV1), angular displacement (DV4), and subjective ratings.

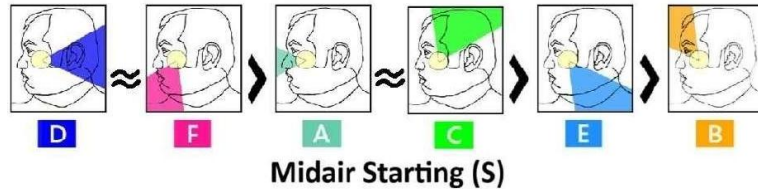
RQ3 Results: 6 Region Layout



RQ3 Results: 6 Midair Pattern

Starting over Ear (D), Chin (F) and Nose (A), Avoiding Eye (B)

$$D \approx F > A \approx C > E > B$$



D / F: ↑Accuracy, ↓Displacement; stable initiation

A / C: good accuracy within FOV, mild directional bias

E: limited visual feedback

B: ocular avoidance, lowest accuracy

Figure : Relative performance of 6 swipe regions across interaction spaces. Arrows indicate metric trends contributing to the ranking (Accuracy / Ranking ↑ higher & Displacement ↓ lower is better). Accuracy = DV1, Angular Displacement = DV4, Ratings = Subjective swipe region ratings.

6 Region Segmentation				
Unidirectional		Angular		
Axial	Nonaxial	U-Shaped (180°)	V-Shaped Medium (30°)	V-Shaped Large (60°)

Swipe Group	Stable	Moderate	Unstable	Observation
Axial	AD DA	-	-	Stable on cheek–chin axis; lowest deviation
Non-axial	CF FC	EB	BE	Stable toward F; B, E weaker
U-shaped (180°)	AA, DD EE, FF	BB CC	-	U-shapes mostly stable; B / C less consistent
V-shaped Medium (30°)	CD, DC FA	AF, FE, EF DE, ED	AB, BA BC, CB	Stable near D; Upper-face angular swipes weaken
V-shaped Large (60°)	CA, DF BD, EA	AC, AE, FD FB, EC	BF, DB CE	Stable on D–F axis; long B/C/E crossings degrade.

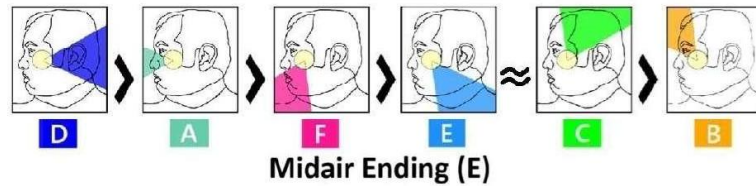
(a) Midair

Figure : Swipe shape stability under 6-region segmentation derived from accuracy (DV1), angular displacement (DV4), and subjective ratings.

RQ3 Results: 6 Midair Pattern

Ending Over Ear (D), Nose (A) or Chin (F), Avoiding Eye (B)

$$D > A > F > C \approx E > B$$



D: ↑Accuracy, ↓Displacement; stable termination

A: strong visual guidance; F: moderate stability

C / E: reduced separability;

B: highest angular skew

Figure : Relative performance of 6 swipe regions across interaction spaces. Arrows indicate metric trends contributing to the ranking (Accuracy / Ranking ↑ higher & Displacement ↓ lower is better). Accuracy = DV1, Angular Displacement = DV4, Ratings = Subjective swipe region ratings.

6 Region Segmentation				
Unidirectional		Angular		
Axial	Nonaxial	U-Shaped (180°)	V-Shaped Medium (30°)	V-Shaped Large (60°)

Swipe Group	Stable	Moderate	Unstable	Observation
Axial	AD DA	-	-	Stable on cheek–chin axis; lowest deviation
Non-axial	CF FC	EB	BE	Stable toward F; B, E weaker
U-shaped (180°)	AA, DD EE, FF	BB CC	-	U-shapes mostly stable; B / C less consistent
V-shaped Medium (30°)	CD, DC FA	AF, FE, EF DE, ED	AB, BA BC, CB	Stable near D; Upper-face angular swipes weaken
V-shaped Large (60°)	CA, DF BD, EA	AC, AE, FD FB, EC	BF, DB CE	Stable on D–F axis; long B/C/E crossings degrade.

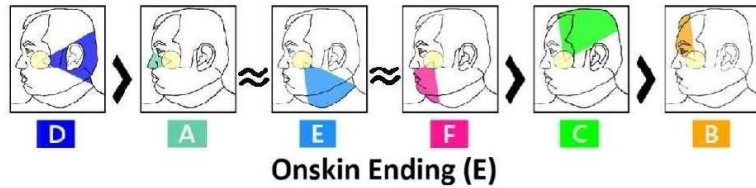
(a) Midair

Figure : Swipe shape stability under 6-region segmentation derived from accuracy (DV1), angular displacement (DV4), and subjective ratings.

RQ3 Results: 6 Onskin Pattern

Starting Positions Avoid Eye (B) and Temple (C) Regions

$$D > A \approx E \approx F > C > B$$



D / A: lowest displacement and highest accuracy

E / F: intermediate endpoints

C: reduced separability

B: highest skew and lowest ratings

Figure : Relative performance of 6 swipe regions across interaction spaces. Arrows indicate metric trends contributing to the ranking (Accuracy / Ranking ↑ higher & Displacement ↓ lower is better). Accuracy = DV1, Angular Displacement = DV4, Ratings = Subjective swipe region ratings.

6 Region Segmentation				
Unidirectional		Angular		
Axial	Nonaxial	U-Shaped (180°)	V-Shaped Medium (30°)	V-Shaped Large (60°)

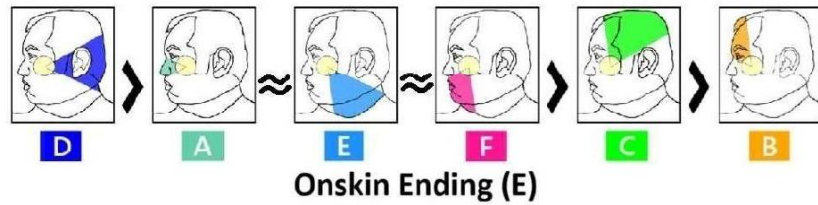
Swipe Group	Stable	Moderate	Unstable	Observation
Axial	AD DA	-	-	Stable on cheek-chin axis; lowest deviation
Non-axial	CF	FC	EB BE	Stable toward F; swipes intersecting B unstable
U-shaped (180°)	AA, CC DD, EE	FF	BB	Stable at A/D/E/F anchors; loops at B unstable
V-shaped Medium (30°)	CD, DC, ED EF, FE	FA, AF DE	AB, BA BC, CB	Stable near D; swipes crossing B unstable
V-shaped Large (60°)	DF FD	AC, AE, CA EA, CE, EC	BD, BF DB, FB	Stable on D-F axis; eye-crossing swipes unstable

(b) Onskin

Figure : Swipe shape stability under 6-region segmentation derived from accuracy (DV1), angular displacement (DV4), and subjective ratings.

RQ3 Results: 6 Onskin Pattern

Ending Positions Also Avoid Eye (B) and Temple (C) Regions



D / A: lowest displacement and highest accuracy
 E / F: intermediate endpoints
 C: reduced separability
 B: highest skew and lowest ratings

Figure : Relative performance of 6 swipe regions across interaction spaces. Arrows indicate metric trends contributing to the ranking (Accuracy / Ranking ↑ higher & Displacement ↓ lower is better). Accuracy = DV1, Angular Displacement = DV4, Ratings = Subjective swipe region ratings.

6 Region Segmentation				
Unidirectional		Angular		
Axial	Nonaxial	U-Shaped (180°)	V-Shaped Medium (30°)	V-Shaped Large (60°)

Swipe Group	Stable	Moderate	Unstable	Observation
Axial	AD DA	-	-	Stable on cheek-chin axis; lowest deviation
Non-axial	CF	FC	EB BE	Stable toward F; swipes intersecting B unstable
U-shaped (180°)	AA, CC DD, EE	FF	BB	Stable at A/D/E/F anchors; loops at B unstable
V-shaped Medium (30°)	CD, DC, ED EF, FE	FA, AF DE	AB, BA BC, CB	Stable near D; swipes crossing B unstable
V-shaped Large (60°)	DF FD	AC, AE, CA EA, CE, EC	BD, BF DB, FB	Stable on D-F axis; eye-crossing swipes unstable

(b) Onskin

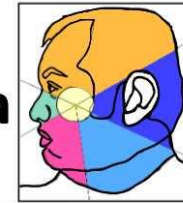
Figure : Swipe shape stability under 6-region segmentation derived from accuracy (DV1), angular displacement (DV4), and subjective ratings.

Proposed 5-Region Layout & Filtered Swipe Shapes

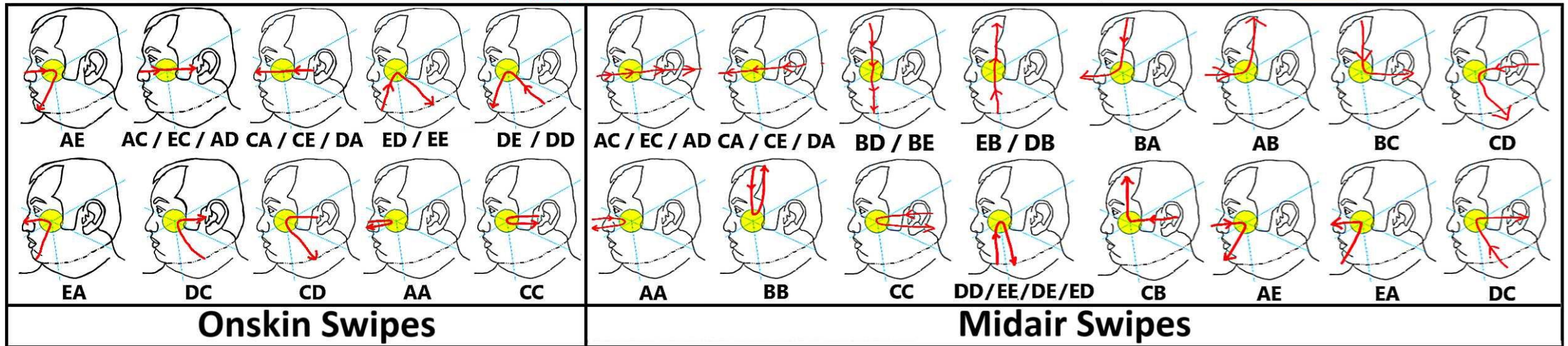
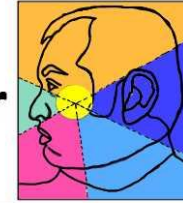
Recommended
5 Region Layout



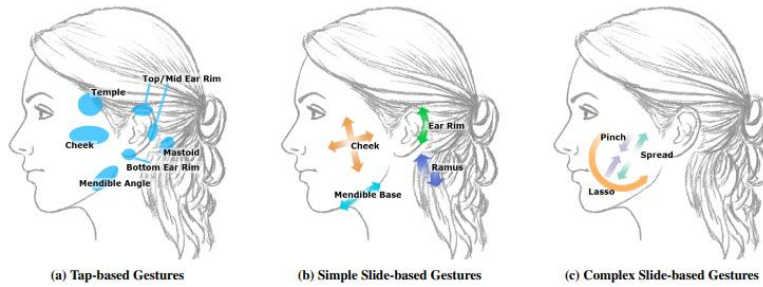
Onskin



Midair



Feasibility of On-Skin Swipe Variations: Prior Work



Earbuddy by Xu et. al. [1] (CHI 2020)

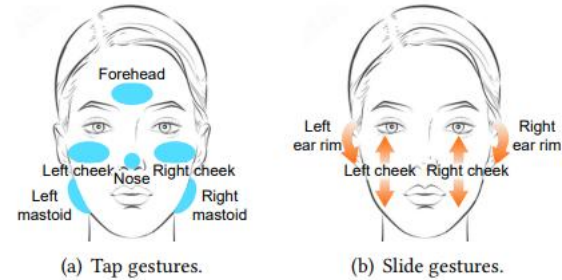


Fig. 14. Hand-face interactive gesture design.



(a) A subject wearing EarACE.

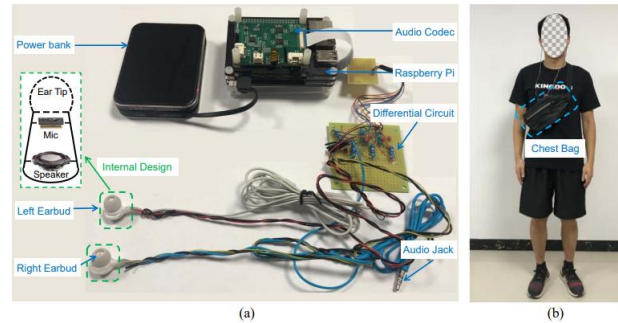
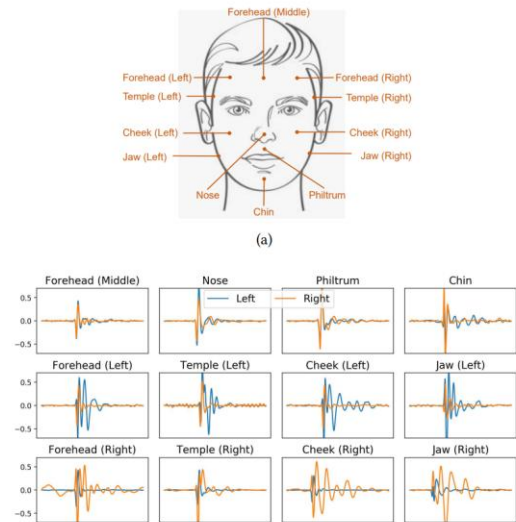


Fig. 8: (a) The developed data recording prototype, (b) illustration of a participant wearing the device.

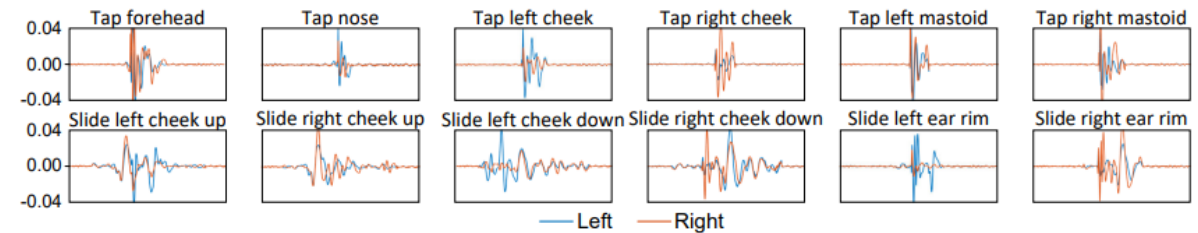


Fig. 15. Snapshots of gesture-induced waveform.

EarAce by Cao et. al. [2] (IMWUT Vol 7 Issue 2)

OESense by Ma et. al. [3] (MobiSys 2021)

Feasibility of On-Skin Swipe Variations: Prior Work

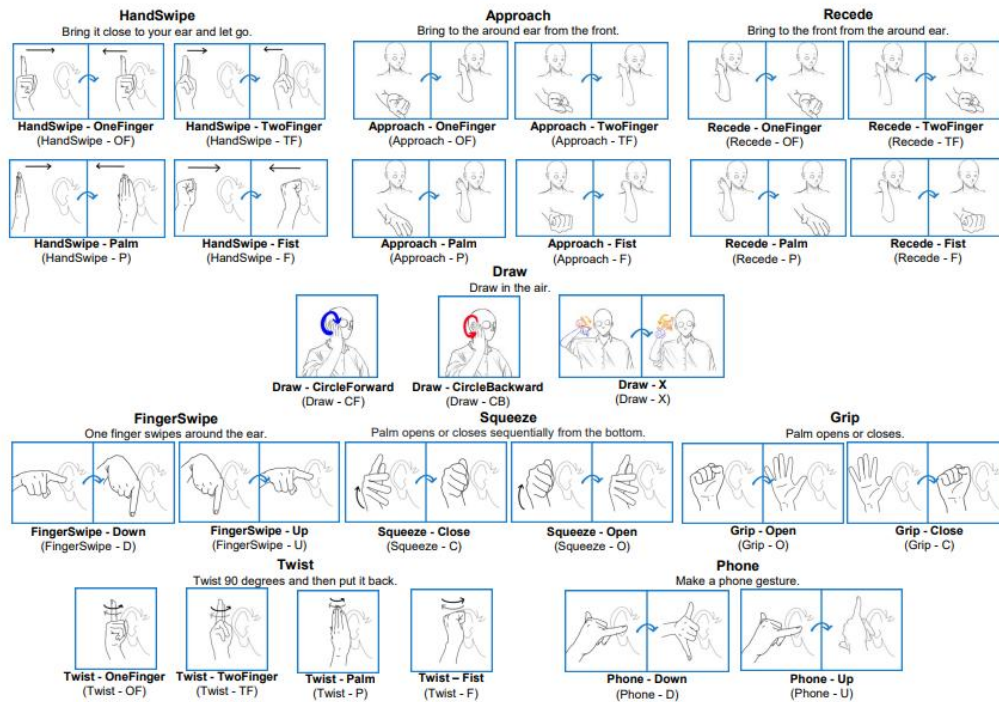
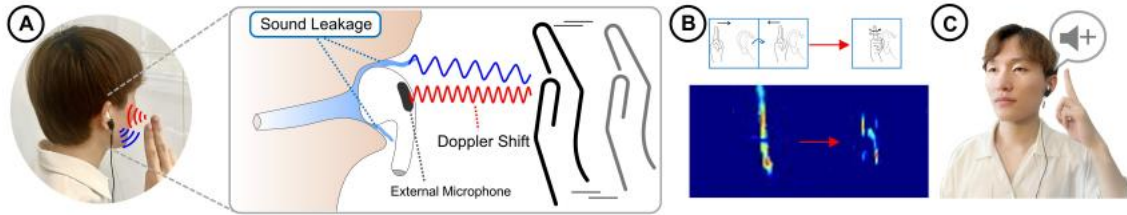
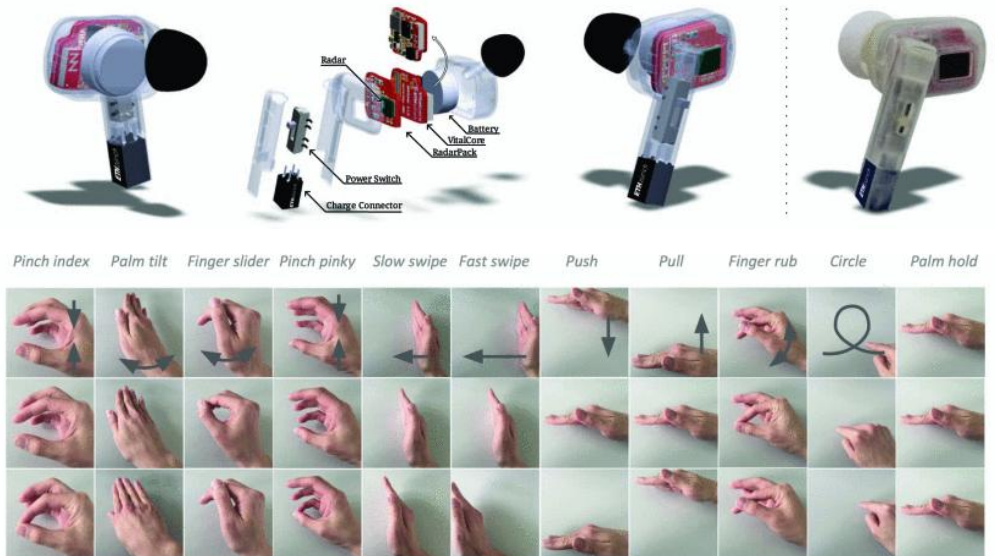


Figure 5: Tested 27 mid-air gestures.



TinyssimoRadar by Ronco et. al. [5] (IoTDI 2024)

EarHover by Suzuki et. al. [4] (UIST 2024)

Exploring Above-Neck Unimanual Swipe Gestures for Off-Device Earable Interaction

Shaikh Shawon Arefin Shimon, University of Waterloo, ON, Canada

Ali Neshati, Ontario Tech University, ON, Canada

Junwei Sun, Ningbo Institute of Digital Twin, Ningbo, China

Qiang Xu, Huawei Technologies Canada Co., Ltd, ON, Canada

Jian Zhao, University of Waterloo, ON, Canada



*AI Disclaimer: Some concept arts in slide 5 & 6 is generated using AI for visual purposes.