Supplementary Materials

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1 ELICITATION STUDY (ES)

In the ES, we prompted participants to suggest the gesture for 14 different referents (animated sequences illustrating the result of interaction with visual representations). Figure 1 shows a small sample of participants and their suggestions, and Figure 2 shows a close–up of an individual participant. Our research team used these videos to calculate agreement rates between suggested gestures for the same referent. We asked participants to keep their hands in the view of the camera for better classification into gesture types and themes.

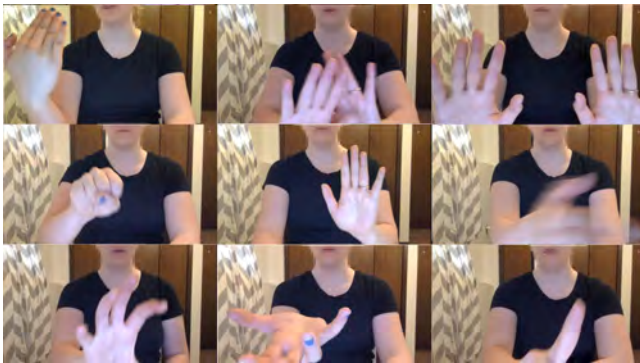Figure 1: A group of participants proposes gestures for referents.

Figure 2: A close–up of an individual participant in the Elicitation Study.

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Table 1 lists questions presented to participants in our Elicitation Study. We ordered tasks to start with simple operations and visualizations (such as hovering and selecting with scatterplot and bar chart) before prompting for gestures for more complex operations such as animated transition. Since the participants were not data visualization experts, some of the referents introduced later in the study were completely new to them (for example, changes over time or transitioning to/from donut chart and barchart).

Table 1: The table shows the ES prompt numbers (Q) that correspond to the numbers of referents in Figure 3, and the columns in Figure 4 that follows.

Questions
Q1. What gesture would you use if you were interested in hovering and selecting in this scatterplot?
Q1.1 What do you think of using the "pinch" gesture for the selection?
Q2. What gesture would you use if you were interested in hovering and selecting in this bar chart?
Q2.1 What do you think of using the "pinch" gesture for selection?
Q3. What is the single gesture you would use to mark objects of interest in this scatterplot?
Q4. What is the gesture you would use to separate this bubble chart into clusters?
Q5.1 What gesture would you use to explore data changes over time in this scatterplot?
Q5.2 What gesture would you use to filter data by Region in this scatterplot?
Q6.1 What gesture would you use to explore data changes over time in this bar chart?
Q6.2 What gesture would you use to filter data by Gender in this bar chart?
Q5.3 and 6.3 Would it be possible to perform both actions (changes over time and filtering) at the same time using gestures?
Q7. What gesture would you use to zoom into a particular cluster?
Q8. What gesture would you use to perform zoom & drag operation with this scatterplot?
Q9. What gesture would you use to perform zoom & drag operation with this bubble chart?
Q8.1 and 9.1 Would you rather use a single gesture to perform zoom & drag operation or multiple gestures in sequence?
Q10. What gesture would you use if you were interested in exploring data outside of the screen area (different timeframe)?
Q11. What gesture would you use if you were interested in rotating the pie chart?
Q12. What gesture would you use if you were interested in rotating the donut chart?
Q13. What gesture would you use to sort this vertical bar chart in ascending/descending order?
Q14. What gesture would you use to sort this horizontal bar chart in ascending/descending order?
Q15. What gesture would you use if you were to perform the transition, from bar chart to donut chart?

Figure 3: Elicitation Study referents. Numbers behind each referent correspond to the prompt number (Q) in Table 1

Figure 3 shows the 14 referents of the Elicitation Study. Numbers in parenthesis correspond to the prompt number (Q) in Table 1. We designed referents to explore the following gesture categories: (1, 2) hovering and selecting; (3) marking items of interest (lasso); (4) reconfiguring data; (5.1, 6.1, 10) exploring changes over time; (5.2, 6.2) filtering; (7, 8, 9) zoom&pan; (11) rotation; (12, 13) sorting; and (14) animated transition. Desired effects were repeated and shown across different visual representations (e.g., selecting a data point on a scatter plot (Q.1) and a bar–chart (Q.2)) to explore if elicited gestures were influenced by the visualization type itself.

1.1 ES Results

Figure 4 shows participants' suggestions for prompts (Table 1) and referents (Figure 3) presented in our Elicitation Study. The figure shows individual suggestions for each gesture effect, with the following properties: *gesture types* (in color) associated with each gesture effect; *gesture themes* grouped for every gesture effect ("grey" shades for the same theme, "n/a" that means no agreement, "no suggestion" means that a participant could not suggest a suitable gesture for the effect presented); *handedness* such as "unimanual," "consecutive unimanual" (e.g., two different gestures performed one after the other with one hand), "unimanual+bimanual" (e.g., unimanual gesture followed by bimanual gesture), "bi-manual synchronous," and "bimanual asynchronous." The bottom row illustrates gestures for a set of similar concepts demonstrated across various tasks for both "horizontal" and "vertical" themes.
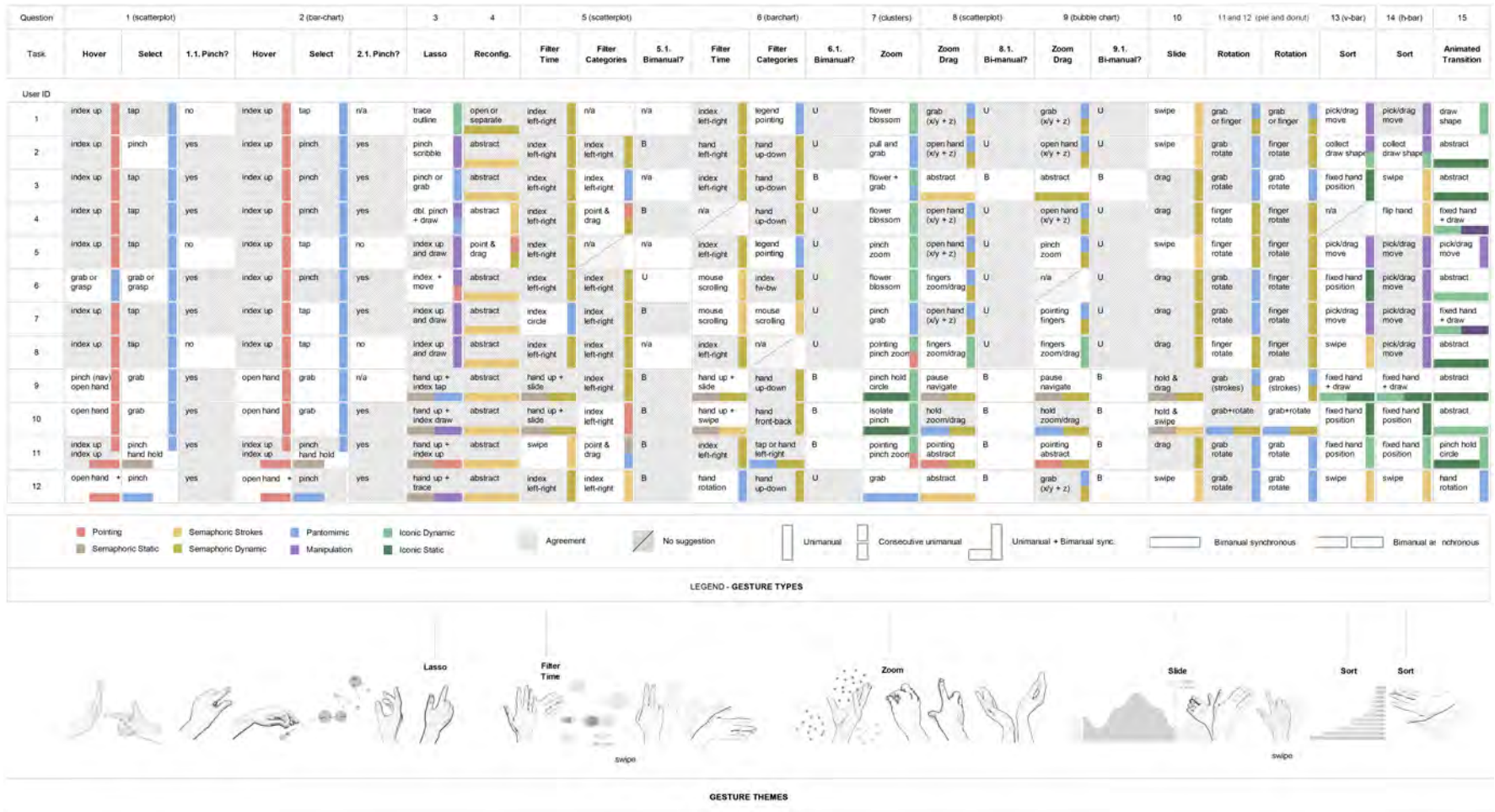

Figure 4: The figure shows individual suggestions for each gesture effect, with *gesture types* (color) and *gesture themes* grouped for every gesture effect.

1.2 Post–ES Survey

This section focuses on survey questions following the ES. Table 2 displays the post–ES survey questions, while Table 3 reflects participant feedback or relevant comments regarding whether or not they would recommend the mid–air gesture system to others. Figure 5 shows the answers to the post–ES survey questions answers to the following questions Q1–Q7.

Table 2: Post–ES survey questions.

Questions
Q1. Of the following, which do you use most often? - PC (Windows) - Mac (iOS) - Other
Q2. Of the following, which do you use most often - Desktop - Laptop - Other
Q3. Of the following, which do you use most often when using a computer (laptop or desktop)? - Mouse - Trackpad - Other
Q4. Do you use a tablet (e.g., iPad, Galaxy, Fire, et al.) for personal and/or professional use? - Yes - No
Q5. What make of smartphone do you use? *Two distinct answers provided:* *iPhone and Samsung Galaxy.*
Q6. Based on your own experience(s), can you imagine using mid–air gestures in your life and/or work? - Yes - No - Other
Q6.1. If "yes" to the question above, use this space to elaborate *Limited answers provided:* *I can imagine using them to interact with digital resources of various sorts, particularly since most of my work is done on the computer.* *I'd use it for controlling home systems, especially home management systems, as well as cooking devices, entertainment, and communication.* *Visualizing inside a property*
Q7. Based on your own experience(s), would you recommend mid–air gesture manipulations systems to others? - Yes - No
Q8. Please use this space to reflect or offer feedback on your elicitation study experience or any other relevant comments. *Answers provided in Table 3*

Table 3: Comments provided to the Q8 post–ES survey question.

| *Please use this space to reflect or offer feedback?* |
| --- |
| I could see this type of tool being interesting/useful for data analysts or policy professionals |
| Additionally, I think it could make for dynamic and fun teaching tools for educators at both the K–12 and college levels! |
| Good luck with the study! I'm interested in the results |
| I think the mid–air gesture concept is too new to us. I think once systems are designed that facilitate that kind of interaction, we'd get used to it |
| It sounds like it might be useful at some point and I don't doubt that I might use it some day, but it isn't on my radar right now. |
| This study was a good opportunity to think about the types of mid–air gestures to use. |
| I didn't have enough experience with the system to say one way or the other. |
| Great learning experience. |
| Yes, to try to provide better explanations. |
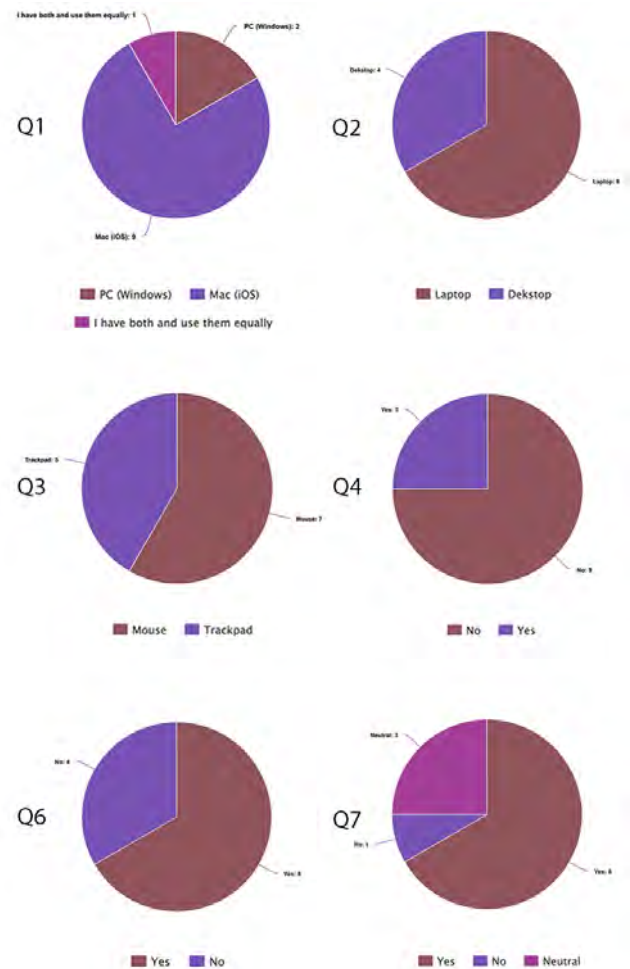
Figure 5: Post–ES survey answers to the following questions: Q1, Q2, Q3, Q4, Q6 and Q7.

2 DESIGN SPACE

Table 4 shows the design space dimensions for designing gesture vocabulary. The highlighted rows illustrate the need for disambiguation as well as how gesture types and themes can be accounted for an appropriate redesign. Methods describe how tasks are carried out and establish a link between the operations of elicited and designed gestures.

Table 4: Leveraging gesture types and themes to design gesture vocabulary.

GESTURE DESIGNED	GESTURE TYPE	GESTURE THEME	INTERACTION METHOD
HOVER	Pointing	Index up	Explore datapoints
SELECT	Pantomimic	Pinch, closing index and thumb	Mark something of interest
RECONFIG.	Sem. Strokes	Bimanual strokes	Reorder data
ZOOM&DRAG	Pantomimic	Grab&drag	Navigate
SWIPE	Sem. Strokes Manipulation	Horizontal theme	Filter features
SLIDE	Sem. Dynamic	Index slide	Filter time
Z–PAN	Manipulation	Index hand move	Filter categories
ROTATE	Sem. Dynamic	Turning the nob	Change view

3 USER STUDY (SS)

All user study participants (20) received temporary Leap Motion Controller devices, which were mailed to their provided addresses. In addition, prior to their scheduled user study session, we provided participants with links to instructions developed by our research team for setting up their Leap Motion device. We used Zoom to record the user study sessions and asked participants to think aloud. We asked participants to show their hands for each gesture in front of their cameras for our research team to review later. A demonstration of the participant in the SS is presented in Figure 6.

Figure 6: Participant in the User Study.

Figure 7 shows the tutorial that introduced participants to gesture vocabulary through the use of a simple web–based application. Initially, we asked participants to comprehend the position of their hands in space or to seek out the "sweet spot." We instructed participants to place their hands over the Leap sensor so they could see their "virtual hands" as they moved them on the screen. The remaining tutorial sections focused on gesture vocabulary. Participants followed instructions on how to perform gestures, and moderators offered suggestions (without making gestures) if they became confused.
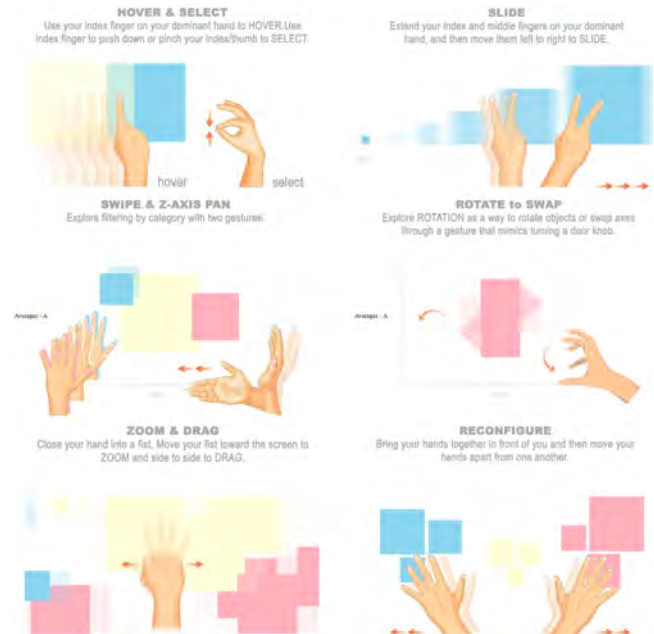

Figure 7: Gesture explanations in the tutorial.

We emailed consent forms to all user study participants, which they read, signed, and sent back prior to their session. Participants received $25 Amazon gift cards for taking part in the study. Figure 8 show one of the SS participants performing gestures on *Gapminder* visualization, and Table 5 gives more details about the post–study survey questions.
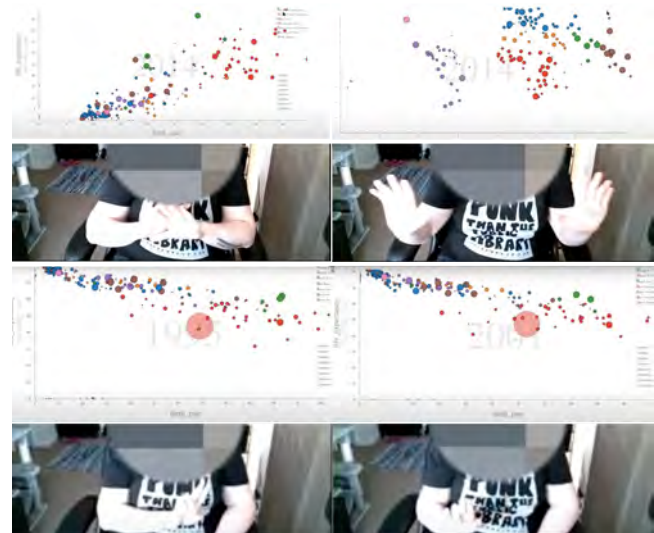

Figure 8: A single participant is performing gestures in our User Study using *Gapminder* visualization.

GESTURE

Q7.1. HOVER/SELECT + ZOOM&DRAG
Q9.1. ROTATE + Z-PAN

RECALL (p=participant, ✔= first guess)

participant #7 (p07)

p01 p02 p03 p04 p05 p06 p07 p08 p09 p10 p11 p12 p13 p14 p15 p16 p17 p18 p19 p20

QUESTIONS

Note: There are multiple questions pertaining to bimanual manipulation, besides RECONFIGURE.
Follow the color scheme for additional information.

GESTURE	RECALL	QUESTIONS
HOVER/SELECT	✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔	**Q1.** Select a data point for a country from Sub-Saharan Africa (red). (this question assumes users will perform hover, before making a selection).
SLIDE	✔ ✔ ✔ ✔ ☒ ✔ ☒ ☒ ✔ ✔ ✔ ✔ ☒ ✔ ✔ ✔ ✔ ✔ ✔ ✔	**Q2.** With that country selected, now we want to explore data in another decade, the 2000s. What gesture would you use to explore this data?
SWIPE	✔ ✔ ✔ ✔ ✔ ✔ ☒ ☒ ✔ ✔ ✔ ✔ ☒ ✔ ✔ ✔ ✔ ✔ ✔ ✔	**Q3.** Now we are interested in changing the category along the y-axis from life_expectancy to mortality_rate. What gesture would you use to make this change?
SLIDE Q7.1.	✔ ✔ ✔ ✔ ✔ ✔ ☒ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ☒ ✔ ☒ ✔ ✔	**Q4.** With this new data set on the y-axis, navigate to a year in the 2000s. (this is the second question regarding "slide" gesture)
Z-PAN	✔ ☒ ✔ ✔ ✔ ☒ ✔ ✔ ✔ ✔ ✔ ✔ ☒ ✔ ☒ ✔ ✔ ✔ ✔	**Q5.** What region has the lowest birth rate in the year you've selected? (this is the first question regarding "z-pan" gesture)
RECONFIGURE	✔ ✔ ✔ ✔ ✔ ✔ ☒ ✔ ✔ ✔ ✔ ✔ ✔ ☒ ✔ ✔ ✔ ✔ ✔ ✔	**Q6.** We want to reorganize data into groups by region. What gesture would you use to reorganize the data in the visualization? What do you see?
ZOOM&DRAG	✔ ✔ ✔ ✔ ☒ ✔ ☒ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ☒ ✔ ☒ ✔ ✔ ✔	**Q7.** In this view, some data points are outside of the visualization. We want to explore the data specifically in Europe and Central Asia. What gesture would you use to see all the data for that region (blue)?
ROTATE Q9.1.	✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ☒ ✔ ✔	**Q8.** In this visualization, we are able to identify certain trends based on the data that you see here. We want to see if there are other trends by changing the orientation of the visualization. What gesture would you use to swap the axes to do this?
Z-PAN	✔ ☒ ✔ ✔ ☒ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ✔ ☒ ✔ ✔ ✔ ✔ ✔	**Q9.** We see data for Europe and Central Asia, but we want to see data for Sub-Saharan Africa. What gesture would you use to filter the data by that region? Can we filter the data by region while changing the visualization's orientation?

Figure 9: Efficacy rates of gesture recall. The figure provides details on the possibility of parallel inputs and individual participants' rates.

3.1 SS Results

Figure 9 shows the recall success rates, which are indicated by a check mark if the participant correctly remembered the gesture on the first try and an X if they did not. The majority of gestures, with the exception of the Z–PAN gesture, have high recall rates. It's interesting to see how individual recall rates vary (for example, participant number 7, highlighted in red, compared to others). Participants who struggled to recall the Z–PAN gesture also struggled to recall other gestures (due to the sensor's input range); other participants failed to recall the Z–PAN gesture when asked a second time (Q9), owing to the exhaustion of the Z–PAN gesture in previous tasks (Q5). Figure 9 also depicts the follow–up questions for bimanual manipulation. Post–User Study (Post–SS) survey questions and answers are presented with Table 5, Figure 10, Table 6, and Table 7

Table 5: Post–SS survey questions, Q1.–Q4. The following questions are based on participants' experience with interacting with the novel data visualization using mid–air gestures in the user study.

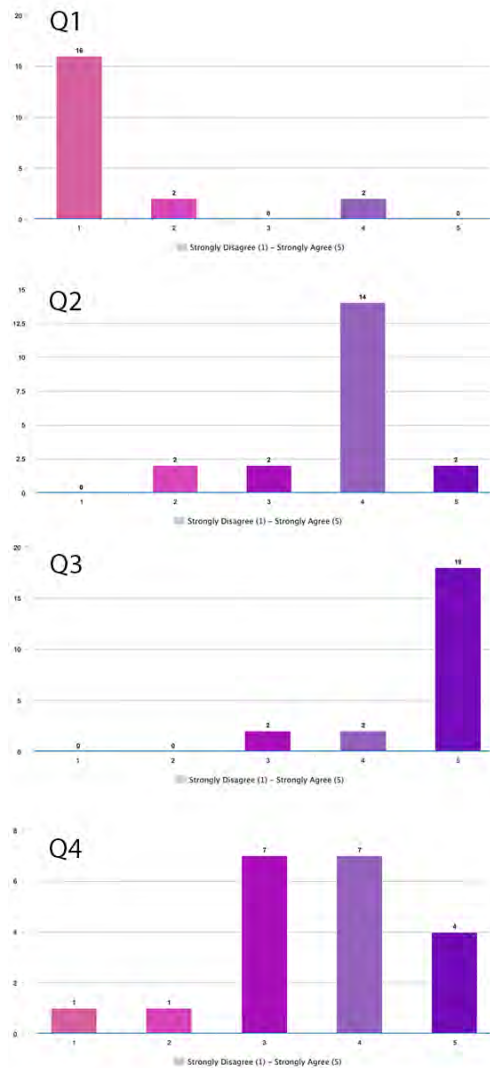| Questions |
|---|
| 1 2 3 4 5 |
| Strongly Disagree ○ ○ ○ ○ ○ Strongly Agree |
| Q1. I found interacting with the data visualization using mid–air gestures unnecessarily complex in completing the tasks. |
| Q2. I found using mid–air gestures very easy to use in completing the tasks. |
| Q3. I liked using mid–air gestures to navigate the data visualization. |
| Q4. Most people would learn to use this method of interaction very quickly. |

Figure 10: Post–SS survey answers to questions, Q1–Q4.

Table 6: Post–SS survey questions and answers, Q5., Q6., Q7. The following questions center on the participants' interactions with the novel interaction modality as well as their backgrounds.

Questions and *Answers*

Q5. What do you like about using mid–air gestures to interact with the data visualizations?
Because it is new technology, it is more fun than what I'm used to.
I like it because it seems like you can do a lot more visualizations of data very quickly than by using typical mouse and keyboard technologies.
You can view the data in a variety of ways in just seconds, without having to go back to the raw data or configure the settings.
More on touch with your body and less in your own mind.
I liked the ease of hand motions and the potential uses for this technology.
It's a very organic method of navigating data and feels pretty intuitive
(although I think if I was learning to use it for work or school, I would keep a cheat sheet until I remembered the gestures better!)
The gestures felt very intuitive and matched how you would move data if it were in front of you on paper.

Q6. What do you dislike about using mid–air gestures to interact with the data visualizations?
Sometimes the device would lose track of my hands and it was frustrating to get it to detect them again.
Sometimes Leap Motion would think I was gesturing something else and so it would do a different command than I wanted it to.
the location needed has to be a certain height for interaction to work
It's censor dependent, so if that isn't functioning then it highly impacts the entire thing.
My computer wasn't quite up to the task, and so the gestures often didn't get read properly, making it a bit harder for me to learn them.
It is difficult to move your hand away without further manipulating the data.

Q7. How would you improve this system?
I would have the gestures drawn out or photographed and explained so users can reference them while they are interacting with the device.
Something similar to the tutorial but on a document so users always have it in front of them while using the application.
Tutorial should include the "vocabulary" of signs too prepare for their application.
Have a "refresh" or reset for the censor so you can reconfigure it if it is malfunctioning.
Such as holding hand up flat to re–calibrate.
Have a "refresh" or reset for the censor so you can reconfigure it if it is malfunctioning.
Such as holding hand up flat to re–calibrate.
I would have the gestures drawn out or photographed and explained so users can reference them while they are interacting with the device. Something similar to the tutorial but on a document so users always have it in front of them while using the application.
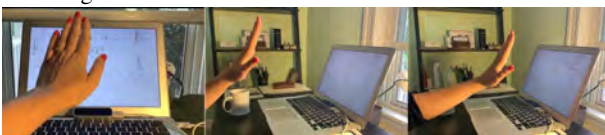
Table 7: Post–SS survey questions and answers, Q8.–Q12. The following questions center on the participants' interactions with the novel interaction modality as well as their backgrounds.

Questions and *Answers*

Q8. Narrate your experience as you would explain the interface to your friend. Would you recommend it to them for exploring data visualizations?
Once some of the kinks are worked out, I would definitely recommend it.
You can work through the data in a much more organic way, the way you would a physical object.
The interface requires your thoughts to communicate with your hands in a detailed "conversation"
I used hand gestures to explore data like you often see in Marvel movies/high tech film. I would recommend it to them.
This interface allows you to look at data visualizations and alter them simply by using your hands and gesturing with them
There are a few different hand gestures that allow you to manipulate data visualizations so you can change the way you view the data on your screen
I would recommend it to them because it makes viewing huge sets of data much easier and it is not very difficult to learn the gestures.
I felt like I understood the gestures well, and what they would do, after practicing them each two times.
I would recommend this to someone for exploring data visualizations. It was very intuitive and I feel that manipulating the data in this semi–physical way may help them to see new patterns in the data.

Q9. Can you think of another way in which you would use gesture technology?
One way is to use the computer just for basic tools, such as Internet browsing.
You can use your hands instead the mouse to command specific things, such as closing an application window.
It also seems like a great technology to use when editing photos or videos.
For example, if you're editing a video, you can use the swiping timeline gesture to move forward or back in the video timeframe.
left and right hand gestures could "increase" the vocabulary.
For planning/architectural/blue print.
You can use your hands instead the mouse to command specific things, such as closing an application window. It also seems like a great technology to use when editing photos or videos.
you can use the swiping timeline gesture to move forward or back in the video feed.

Q10. What is your gender?
☑ 18-24 ☑ 25-35 ☑ 36-49 ☐ 50-64 ☐ 65+

Q11. What is your age?
☑ Female ☑ Male ☑ Non-binary ☐ Prefer not to answer

Q12. Prior to participating in this study, have you had any experience with gesture technology? *(all answers "no")*

4 EXPERT STUDY (XS)

In an expert study, we evaluated the ergonomics of designed gestures. We asked expert participants to examine their hand postures and movements and provide feedback on reducing hand fatigue. Table 8 shows the video recordings presented to experts, and Table 9 shows the questions asked for each of the eight gestures in the vocabulary.

Table 8: XS video recordings presented to experts. Table 9 (Q4.–Q11.) lists questions asked for each gesture presented below.

Questions
HOVER gesture (index finger up; pointing)
SELECT (pinch) gesture
SLIDE gesture (two fingers up; move left–right)
SWIPE gesture
ZOOM&DRAG gesture ("grab" and "move")
Z–PAN gesture
ROTATE gesture
RECONFIGURE gesture (regroup or cluster data)

The questions presented with Table 9 helped us understand the ergonomics of gestures in the vocabulary. To help explain the posture of each gesture, we present the video with additional images. Please

note that each gesture could be performed with or without the elbow resting on the table, using the dominant hand (left or right).

Table 9: XS questions we asked for every gesture in the vocabulary.

| Questions |
| --- |
| Q1. Are you an expert in HCI? *(all answered 'yes')* |
| Q2. Do you have experience with hand gesture–based interfaces? *(eight answered 'yes')* |
| Q3. Do you have experience with information visualization? *(all answered 'no')* Please, watch the video showing the hand gesture and its effect. *(applies to each gesture presented with Table 8)* Please use the following scales to assign scores for the gesture. |
| Q4. User posture (the position in which someone holds their hand). Does the hand position relative to your body give you any discomfort? Please rate the level of difficulty. Link it to physical feelings.

 hard 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ easy |
| Q5. Any additional comments about the posture? |
| Q6. Muscle use (strain or fatigue). Does the position cause muscles to tense up in an uncomfortable manner?

 hard 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ easy |
| Q7. Any additional comments about muscle use? |
| Q8. Wrist movements and/or hand position

 hard 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ easy |
| Q9. Any additional comments about wrist movement or hand position? |
| Q10. Are there any other factors that contribute to or detract from a user's well–being? (yes or no, if yes, what are they) |
| Q11. Please rate "other factors" ONLY if any listed with the previous question. Otherwise, proceed to the next section.

 hard 1 ○ 2 ○ 3 ○ 4 ○ 5 ○ easy |

4.1 XS Results

We discuss the tradeoffs between the memorability and ergonomics challenges of designed gestures in the manuscript. HOVER and SELECT gestures, in particular, have the highest memorability rates, but face minor ergonomics challenges. Specifically, the ergonomic challenges are related to two attributes: hand posture and wrist movements. Figure 11 depicts the rates of posture and wrist movement for the HOVER and SELECT gestures. This pattern (high recall and low ergonomics score, and vice versa) is also observed in gestures that are not significantly influenced by legacy bias.

User posture (the position in which someone holds their hand). Does the hand position relative to your body give you any discomfort? Please rate the level of difficulty. Link it to physical feelings.
14 responses
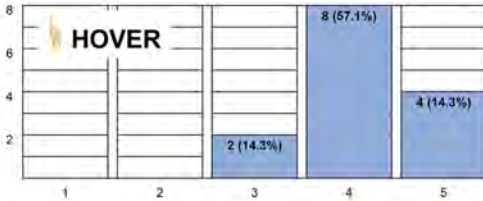
Wrist movements and/or hand position
14 responses
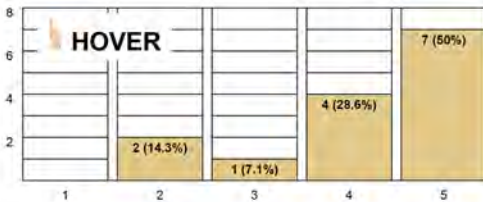
User posture (the position in which someone holds their hand). Does the hand position relative to your body give you any discomfort? Please rate the level of difficulty. Link it to physical feelings.
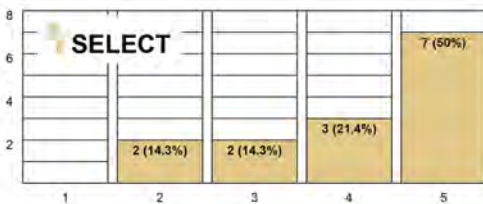14 responses
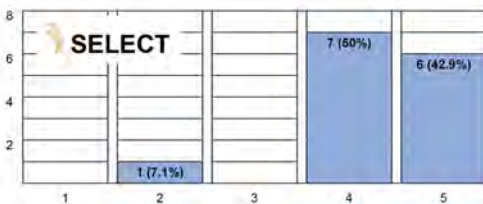
Wrist movements and/or hand position
14 responses

Figure 11: XS study ratings for users' hand posture and wrist movements for the HOVER and SELECT gestures.

In contrast to HOVER and SELECT, Z–PAN had the lowest recall score and the highest rates for ergonomics characteristics. Figure 8 shows the Wrist movement ratings for Z–PAN gesture. Figure 12 shows gesture ratings for Z–PAN gesture in the XS study.

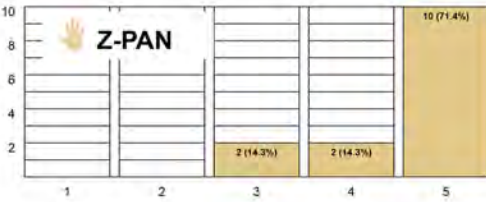Wrist movements and/or hand position
14 responses

Figure 12: Wrist movement rating for the Z–PAN gesture.