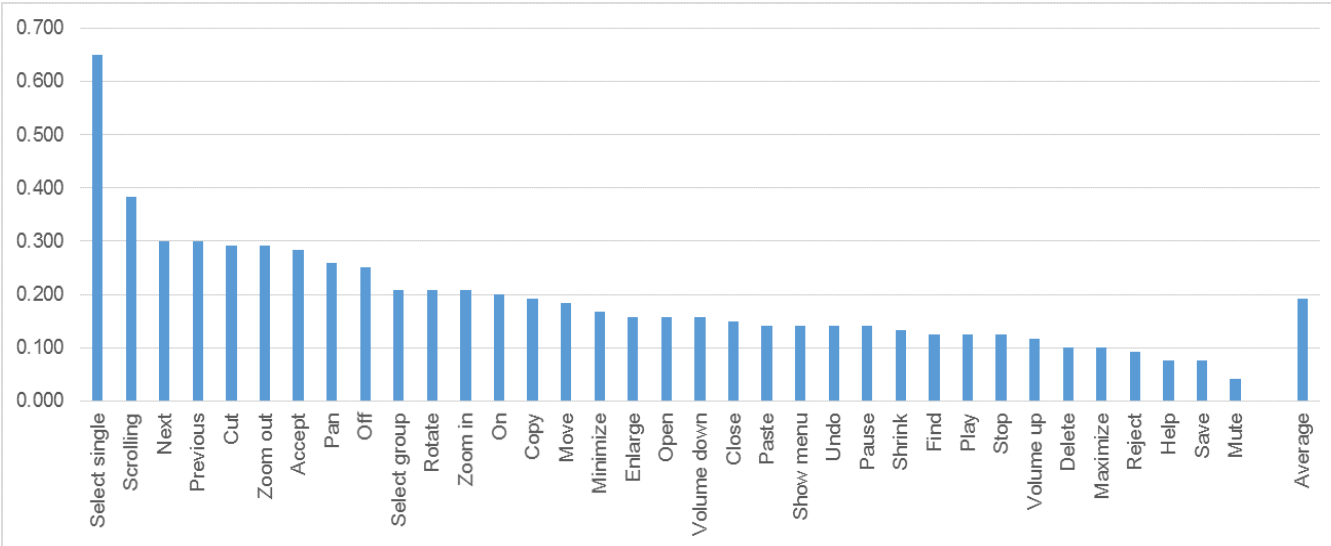

Figure 4: Agreement rates for the 34 referents.

approach defined above, we were able to reduce the set to 47 unique gestures. By taking the maximum consensus gesture for each referent in this set, we were left with 8 unique gestures, which represented 220/544 gestures or 40.4% of the entire set.

Agreement Between Participants

Previous studies [10, 17, 23, 29] used Wobbrock *et al.*'s Agreement Rate formula [28], which did not accurately represent gestures with no agreement. Gestures that had zero agreement trivially agreed with themselves. Therefore, gestures with zero agreement actually did not have an agreement rate of 0. This formula also did not account for the degrees of freedom; a gesture with 15/20 matching entries had the same agreement rate as a gesture with 30/40 matching entries, despite the latter clearly showing greater agreement for the consensus gesture [25].

A new agreement rate formula was proposed by Vatavu *et al.* [25], which accounts for the missing factors in the old formula. We measured agreement between participants using this new formula and the accompanying AGATe (AGreement Analysis Toolkit) software. The revised agreement formula is defined in Equation 1:

$$AR(r) = \frac{|P|}{|P|-1} \sum_{P_i \subseteq P} \left(\frac{|P_i|}{|P|} \right)^2 - \frac{1}{|P|-1} \qquad (1)$$

where "P is the set of all proposals for referent r, $|P|$ the size of the set, and P_i subsets of identical proposals from P" [25].

Agreement rates ranged from 0.042 (low agreement, $AR \le 0.100$) to 0.650 (very high agreement, $AR > 0.500$). The mean AR was 0.191 (medium agreement, $0.100 < AR < 0.300$). The agreement rates of all referents are shown in Figure 4. Since the new formula calculated *AR* less optimistically, Vatavu *et al.* recalculated the *AR* of 18 previous studies [25]. In these studies, the average sample size was 19.1, while mean *AR* was 0.221.

Along with a new formula for agreement rate, Wobbrock *et al.* also introduced the Coagreement Rate, which looks at "how much agreement is shared between two referents r_1 and r_2." This is interesting because we can observe patterns previously left unnoticed. Existing work had already shown a significant relationship between gestures of dichotomous pairs [17, 23, 29] such as "Next"/"Previous" or "Zoom In"/"Zoom Out". Most of the pairs described were directional, where consensus gestures opposed each other directionally *(e.g.*, swipe left/right). Less focus has been placed on toggles such as "On"/"Off" or "Play"/"Pause". With the new Coagreement Rate, we not only found that "On"/"Off" (as well as "Play"/"Pause") have the same consensus gesture, but that participants who picked one gesture in r_1 often picked the same gesture in r_2. We know this since the *AR* for r_1 and r_2 are close to $CR(r_1,r_2)$. For example, $AR(\text{On}) = 0.200$, $AR(\text{Off}) = 0.250$, and $CR(\text{On,Off}) = 0.197$. This is different from only knowing that the same number of participants picked the consensus gesture in both referents, and suggests referents of this type should use the same gesture.

Consensus Gesture Set

As mentioned earlier, the original gesture set was reduced to 8 unique gestures. This set is rather small and even within each of the six categories of referents, there were conflicts where one gesture was preferred for several referents. This was an expected outcome, since we classified five fingers with only two types: two fingers or less, and three fingers or more. To resolve the conflicts, we looked at each instance of the consensus gesture for each referent and identified which fingers were used most. The idea behind this resolution comes from observing the participants. While participants often mixed up the exact finger they suggested for a gesture, there was a recurring theme of choosing similar gestures for seemingly related tasks. Several participants exhibited this pattern when choosing gestures for “Cut”, “Copy”, and “Paste”, as well as “Accept” and “Reject”. We observed a strong preference for keeping these gestures “close to each other” or “next to each other”.

Sometimes participants arbitrarily chose different fingers for a similar gesture (such as tapping any finger and the thumb together), when they had difficulty coming up with three meaningful gestures. We tried to reduce this source of randomness by taking the most used finger(s) for each consensus gesture. Very interestingly, assigning fingers with this procedure resolved all but one conflict in the consensus gesture set.

The only remaining conflict was between “Stop”, “On”, and “Off”. Since the top two preferred gestures for each of these referents were the same (make a fist, or tap the index/middle/ring ringers on the palm), we included both gestures for all three referents. We suggest using the same gesture for both “On” and “Off”, as we previously mentioned a significant Coagreement Rate between the two. The resulting consensus set of 16 gestures representing 35 referents in 6 categories is shown in Figure 5.

Figure 5: Consensus Gesture Set

Actions

To better understand the distribution and makeup of the gestures elicited, recall our classification method which separates gestures by actions, based on Bill Buxton's work on *Chunking* and *Phrasing* [2]. When we examined the actions chosen for consensus gestures, we discovered several motifs.

Of the four action types, *Taps* were the most common (19 of 34 referents). During the think-aloud sessions, users offered some potential reasons for picking *Taps*. *Taps* were popular amongst users because of their ease with which they can be performed and their conceptual simplicity, making them easy to reproduce. Many *Tap* gestures were also preferred due to their resemblance to interaction with other devices, such as mice, trackpads, gaming devices, or remote controllers. This is apparent in the *Selection* category, where all three consensus gestures used *Taps*. A *Tap* gesture provided the precision desired when selecting a specific set of objects.

Swipes (14 of 34 referents) were frequently used when the task involved picking a value inside a continuous range, such as turning the volume up or down. In many cases they reminded users of the fluid action of sliders or radial dials. *Swipes* were also often used for tasks that were directional, such as moving something or scrolling in any direction. Of the six referents in the *Transforms* category, five made use of *Swipes.* The "Rotate" task used a *Circle* action, which was likely chosen due to the circular motion associated with rotation.

The *Draw* action appeared with six of the participants, but did not make it into the consensus set. Although drawing a question mark for "Help" or drawing an 'X' for "Close" seemed more intuitive and easier to recall, participants only resorted to the *Draw* action when experiencing difficulty devising three gestures.

Compounds gestures made up 12% of all gestures elicited, and were preferred for approximately 10% of tasks. These were mostly used for tasks that users instinctively split into smaller modules. For example, when asked to select a group of items, a participant said, "I swipe across my fingers like I am choosing the items, then I tap on my fingers to select them." In another example where a participant was asked to perform the *Save* task, the participant responded, "I have something here, then I want to make a copy here to save it."

In Figure 6, we present the distribution of action types in the preferred gestures set. The preferred gestures set represents the preferred gestures of every participant, rather than just the gestures in the consensus set. By examining the graph, we can easily tell which actions were preferred for specific gestures. For example, we can tell that *Swipes* were preferred for dichotomous pairs, which are discussed in more detail later.

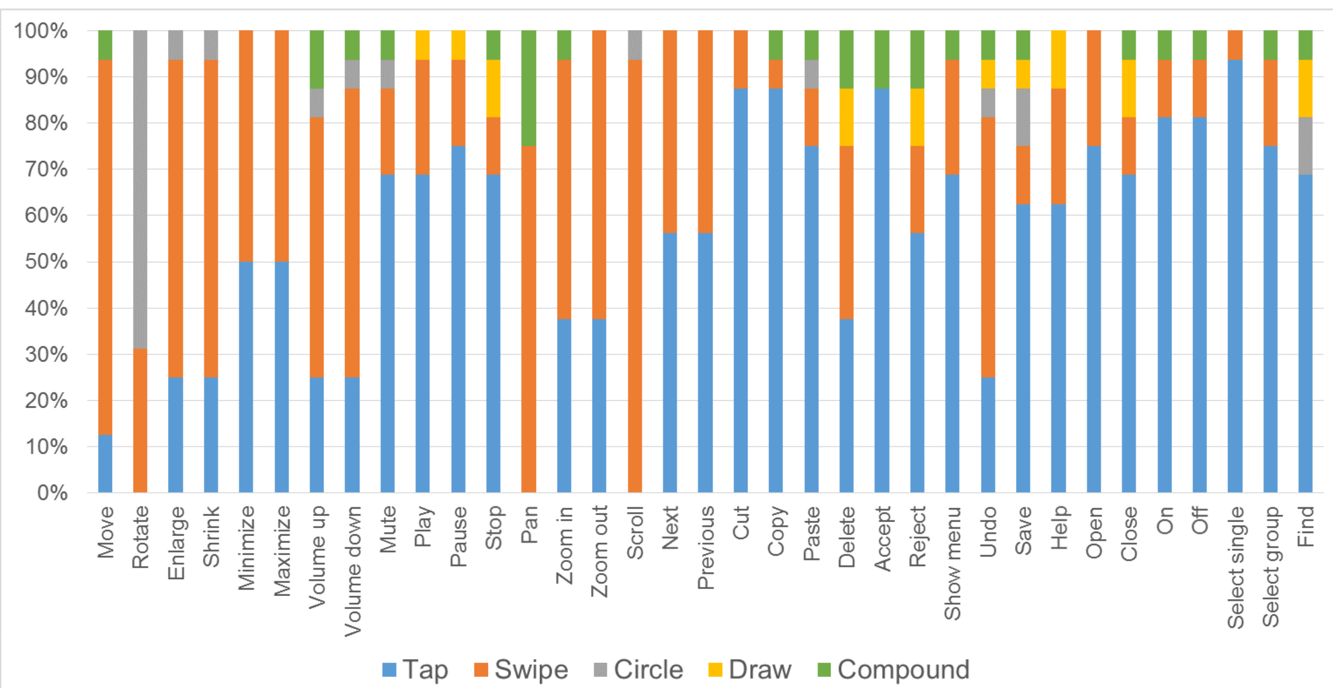

Figure 6: Distribution of action types in the preferred gesture set.

Actors
Given the physical constraints of SHMGs where gestures are performed using only a single hand, it made sense that all gestures were performed using one or more finger(s). Knowing which fingers were most common in our data helps us to quantitatively assert which actors are most suitable for SHMGs. We can then combine qualitative observations from the study with insights from existing work to suggest reasons for some of the actors standing out as most commonly used by participants. The frequencies of each finger appearing in the gestures elicited can be seen in Figure 7.

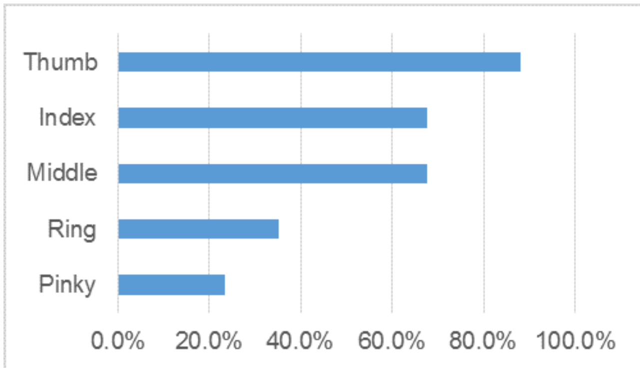

Figure 7: Frequency rates of each finger in consensus set. Sum > 100%, as multiple fingers may be used in a single gesture.

Unsurprisingly, the thumb was involved in 88% of all gestures. As explained by existing work relating hand anatomy and gestures [30], our hands are opposable through the use of our thumbs. Because of this special trait of thumbs, as well as its unique ability to rotate, the thumb can easily touch other parts of the hand, which by definition of SHMGs constitutes a gesture. Whereas other fingers have difficulty interacting with their neighbors, thumbs can touch most areas of the other fingers quite naturally. Capable of rotating, the thumb is often used for controls that involve rotation or multiple axes. For example, many gaming controls use the thumb for the D-Pad or joystick, while (two-dimensional) phone screens are often interacted with the thumb. Similarly, all the elicited *Swipe* gestures were performed with the thumb.

The preference of the index and middle fingers, when compared to the ring and pinky fingers, can also be explained by Wolf *et al.'s* summary of the anatomy of the hand [30]. Due to biomechanics and more specifically the muscles involved in moving each finger, the index finger is most suited to independent movement, followed by the middle finger. The ring finger is considered to be the least feasible, because "two muscles (*M. flexor digitorum profundus & M. flexor digitorum superficialis*) are bending synergistically the index, middle, and little finger to bring them into the palm position. In addition another muscle is responsible for stretching the ring finger (*M. extensor digitorum*), but because this muscle is also responsible for stretching the other fingers and because the ring finger has a physical connection to the middle finger (*Connexus intertendineus*), the middle finger will always move a bit in the same direction as the ring finger does."

While the pinky finger is also able to move independently like the index finger, it was seldom used in the consensus set (2 of 34 referents). Possible explanations include the greater distance between the thumb and pinky finger, as well as the reduced strength of the pinky finger compared to the index finger. Some participants avoided using the pinky finger due to potential discomfort and fatigue.

IMPLICATIONS FOR DESIGN
Combining the results above as well as the results of the interviews conducted with users at the end of each study session, we derived several guidelines for the design of SHMGs.

Previous Experience
While the agreement rate was comparable to existing studies, we believe previous experience of participants strongly affected our results. This motif has been previously documented [23, 26], and generally led to greater agreement amongst participants. However, we found that the previous experience of our participants both positively and negatively affected agreement rates. An example where it contributed positively to agreement is the "Cut" referent, which users easily associated the task with a common symbol for scissors (tapping the index and middle fingers together). In another example where previous experience may have negatively influenced agreement rates, the proposed gestures for "Mute" included using the sign language representation of the letter "m" and also simulating the action of reaching towards the back of a handheld gaming console to reduce volume. While there are physical representations for "Mute", such as a clenched fist in music performances (a gesture that participants had little prior experience with), users drew on a large variety of other previous experiences for such actions. Regardless of whether previous experiences affected agreement rates positively or negatively, the impact of these experiences was apparent in the behavior of participants.

As documented by Nebeling *et al.*, we also noticed a trend where referents which related to physical actions (such as "Cut") resulted in greater recall and agreement when metaphors were used [14]. This observation suggests that gesture designers must consider the nature of each referent, the existing metaphors, and whether these metaphors are commonly used by the expected users of the system. For referents that do not benefit from the use of metaphors, abstract gestures are more suitable as indicated by the numerous cases when users recalled specific details incorrectly.

Fingers and Postures: Their Meanings
Another topic that surfaced in other elicitation studies is the cultural meaning of various hand postures and gestures.

While symbolic hand gestures have already been discussed [23, 26], *e.g.*, "Help" with a beckoning gesture or "Mute" with a clenched fist, we found that users often chose specific fingers as well for a variety of reasons. Besides using the index finger for its dexterity or convenience, users frequently referred to the index finger as the pointer finger, which evoked a feeling of confidence or direction. A particularly interesting case is "Help", where one user used the pinky finger because "pinky is the weaker one, so you need more help."

SHMGs can be discrete and subtle, but we expect these gestures to be performed in both private and public spaces. As such, certain gestures may be less suitable than others and may need to be substituted for specific user groups.

Dichotomous Pairs and State Toggles

Another reason for choosing specific fingers was the motif of dichotomous pairings, and in some cases groupings of three or more gestures. As previously mentioned, dichotomous pairs often resulted in opposing gestures, such as swiping left to symbolize previous and swiping right to symbolize next. In Figure 6, *Swipes* are shown to be preferred for "Enlarge"/"Shrink", "Minimize"/"Maximize", "Volume up"/"Volume down", and "Zoom in"/"Zoom out". As *Swipes* were heavily preferred for dichotomous pairs in the consensus set as well, we again make the recommendation to *Swipes* for these gestures. We also recommend using identical gestures for toggles, such as "On"/"Off". Identical gestures are more suited to toggles than opposing gestures, as we identified a unique problem with hand gestures when applying certain gestures for toggles. A good example is when some users suggested closing their fist to turn the system "On", while releasing their fist to turn the system "Off". Although the gestures are unique, the hand naturally returns to a relaxed state after tension, relating to Buxton's delimitation of atomic gestures through periods of tension and relaxation [2]. As such, performing the "On" gesture results in the "Off" gesture also being performed. This difficulty was encountered for other pairs such as "Enlarge"/"Shrink" or "Volume Up"/"Volume Down", forcing users to choose other gestures.

Level of Detail

Given the variety of Actors and Actions, there are technically hundreds of possible SHMGs. However, while some users went as far as using different joints to differentiate gestures, most users settled for less detail in their gestures. Many users even complained about the lack of gestures available, as one participant described: "It's very limited, (the) amount of things you can do with one hand and touch." The difficulties participants experienced in recalling gestures in detail prompted the classification method used in our study.

One participant worried "some people would be limited in the number of hand gestures they would have based on hand mobility." This was the case for another participant who could not form a clenched fist. The dexterity of users could influence their preference of gestures.

Finally, select users were aware of variables for creating gestures but opted not to use them, as is the case when one participant used double taps instead of holds (long duration tap). The participant preferred double tapping, which felt more reassuring to them than holding a gesture for a specific duration.

Additional Variables

Due to the perceived limitation of gesture variety, users reported two interesting variables that they could potentially control in addition to the suggestions we made. First, they suggested varying the speed at which a gesture is performed. Performing a gesture slowly was perceived to offer finer adjustment, such as when performing the "Enlarge" or "Shrink" tasks. The second variable used varying forces while performing gestures such as closing a hand harder to perform "Stop" instead of "Pause". These variables may enable a larger vocabulary of natural gestures, provided the speed and force can be detected reliably. These user suggestions were made during an interview at the end of the study, and no such gestures were chosen by participants in the elicitation part.

LIMITATIONS

Here we discuss several limitations and potential extensions of our study.

Spatial Extensibility

As seen with the additional variables proposed by users, our current definition of SHMGs may not fully match the mental models of all users. This is after all the specific reason that we consulted users in our elicitation study. Participants were asked to comment on the feasibility of SHMGs as well as the study itself, and all participants commented on not being able to use mid-air spatial gestures. For example, participants asked if they could perform "Move" by tapping the thumb and index fingers together, before moving the whole hand in mid-air.

Although we defined SHMGs as gestures performed on the hand from the wrist to the fingertips, many users would have liked the option of using spatial tracking of the arm itself as well. While larger arm movements may not be suitable for discrete microgestures in public spaces, users frequently proposed small movements or rotations of the arm. This happened despite users being informed during *priming* that such spatial gestures did not fit our criteria, suggesting the desire and possible need for spatial recognition.

Elicitation Methodology

As documented by existing literature [23, 26], legacy bias may have a significant effect on results in an elicitation study. Although we applied *priming* and *production* to offset legacy bias, we encountered the same problems mentioned by Morris *et al.* [11]. That is, there is no way to determine the optimal amount of gestures each user should propose for each referent. In 55% of all cases, users did indeed choose their second or third gestures as their preferred gesture. When later asked why they did not propose gestures that seemed obvious to the researcher, users often replied, “I didn’t even think of that!” However, other users benefited less from production: “I already have a gesture in mind, so thinking of three different ones makes me start grasping for straws, because I already have a solid idea of what I would do.”

Pairing

Pairing was also proposed by Morris *et al.* [11] as another way to reduce legacy bias. With previous user experience and legacy bias having both positive and negative effects on agreement rates, *pairing* may be useful as a means to generate more optimal gestures. In the situation where a single user might run out of ideas and therefore offer arbitrary gestures as their second or third choice, having a partner may help foster additional ideas. When users pick gestures based on personal and unique experiences, a partner would be able to question the generalizability of such a gesture in a consensus set.

FUTURE WORK

To address the above-mentioned limitations, it may be interesting to perform variations of this study to note how additional variables proposed by users would affect the resulting gestures and agreement rates. While we do not expect significantly higher agreement rates when introducing greater variation, the newly available gestures may be more natural for users. Such gestures could improve recall and therefore be more preferable to users.

Specific Domains

It would also by worthy to investigate user preferences in more specific domains suited to SHMGs, such as while in public transit or while performing a primary task. While the inherent nature of SHMGs makes them less susceptible to factors which create social awkwardness [19], developing generic principles that apply universally to all contexts remains a challenge [15]. Further context-specific studies may reveal subtle factors specific to SHMGs that affect the gestures preferred by users.

CONCLUSION

We recognized the potential of single-hand microgestures (SHMGs) in ubiquitous computing amidst current technological developments. To further inform the design of SHMGs we conducted an elicitation study with end users, where we recorded a set of 1,680 gestures. We presented our findings including agreement rates, frequency statistics, and qualitative observations. Based on this we discussed several implications for the design of SHMGs. Our observations can serve both a guideline to future designers of SHMGs, as well as a reference for further studies.

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