Hands as a Controller: User Preferences for Hand Specific On-Skin Gestures

İdil Bostan[1], Oğuz Turan Buruk[1], Mert Canat[2], Mustafa Ozan Tezcan[3], Celalettin Yurdakul[3], Tilbe Göksun[4], Oğuzhan Özcan[1]

[1] Koç University - Arçelik Research Center for Creative Industries (KUAR), Koç University, İstanbul, Turkey
[2] School of Electrical Engineering, KTH Royal Institute of Technology, Stockholm, Sweden
[3] Department of Electrical & Computer Engineering, Boston University, Boston, Massachusetts, United States
[4] Department of Psychology, Koc University, Istanbul, Turkey

ABSTRACT

Hand-specific on-skin (HSoS) gestures are a trending interaction modality yet there is a gap in the field regarding users' preferences about these gestures. Thus, we conducted a user-elicitation study collecting 957 gestures from 19 participants for 26 commands. Results indicate that (1) users use one hand as a reference object, (2) load different meanings to different parts of the hand, (3) give importance to hand-properties rather than the skin properties and (4) hands can turn into self-interfaces. Moreover, according to users' subjective evaluations, (5) exclusive gestures are less tiring than the intuitive ones. We present users' subjective evaluations regarding these and present a 33-element taxonomy to categorize them. Furthermore, we present two user-defined gesture sets; the intuitive set including users' first choices and natural-feeling gestures, and the exclusive set which includes more creative gestures indigenous to this modality. Our findings can inspire and guide designers and developers of HSoS.

Author Keywords

Mobile computing; on-skin input; touch input; skin gestures; elicitation study; two-hand input, free-hand interaction.

ACM Classification Keywords

H.5.2 Evaluation/methodology - Input devices and strategies - Interaction styles.

INTRODUCTION

Increasing presence of electronic devices in daily life enlarges their field of application, driving researchers to discover new interaction modalities for different purposes and use-case scenarios. Among many modalities, recent research emphasizes the on-skin interaction as an input field for remote controlling the devices. These studies indicate that skin can be auspicious as an input apparatus since it is always available with a wide surface area [43,49]. Moreover, gestures performed on skin are claimed to be superior in terms of social acceptance, required physical effort and precision compared to the free-hand/3D gestures [9,15] since their boundaries are more defined as the sensors can clearly recognize when the touch to the skin occurs. Furthermore, skin is also stretchable, enabling interaction styles from a wider range compared to traditional surfaces.

However, most studies who take skin as input surface work on the whole arm or the forearm as the work space. We believe narrowing the focus down to hands yields promising results for privacy, convenience, and efficiency as hands are always available [6], subject to high proprioception [42], require minimal movement [6], thereby socially acceptable [41] and available for producing distinct gestures [1,43] originating from hand properties like hand-posture. Users' preferences on HSoS gestures is an unexplored territory within the HCI field and previous studies did not present user-preferences for skin gestures that can be performed specifically in hand area. Furthermore, most studies work on gestures for specific devices like mobile devices [42], TV Remote Control [6] or smart watches [29,49] while we aim to produce more generalizable and inclusive results for remote controlling of any electronic device.

Another shortcoming of the previous studies is that their user-elicitation methodology was highly affected by other modalities such as the existing touch interaction practices. In a previous study, most of the skin gestures share very similar characteristics to multi-touch gestures [43]. Therefore, novel interaction techniques specific to on-skin gestures are only partially available. We believe that user habits originated from touch screens and similar modalities cause this uniformity and users tend to fall back onto customary gestures when asked to produce new ones. This phenomenon was observed also by [23]. They claim that this "legacy bias" occurs because users do not want to spend too much mental or physical energy during the gesture production process. They propose three potential solutions to this problem, named as "production", requiring the production of multiple gestures; "priming", priming the participants to properties of the new modality before the elicitation; and "partners", grouping multiple participants to produce the gestures.

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In the light of this information, we followed a two-phased user-elicitation methodology to have an understanding of users' preferences. First phase focused on getting users to produce their own, preferred gestures for certain commands [45]. In the second phase, we followed a similar approach to "production" and "priming" methods [23] in which we asked users to propose gestures that were specific solely to this modality, considering the capabilities of hand and skin like elasticity or different hand postures. Therefore, in addition to most preferred intuitive gestures, we also introduce exclusive gestures. A total of 957 HSoS gestures were collected from 19 participants for 26 different tasks. We analyzed the produced gestures for their various characteristics, certain qualifications as perceived by the users and their agreement scores based on Wobbrock et al.'s formula. We required usage of two hands as most of the implemented technologies for on-skin input need two-handed interaction [6,11,42,43,49]. Although some studies also investigated one-handed on-skin gestures, these are usually referred to as micro-gestures [18,19,44,47] and do not provide a diverse set of gestures because of the limited reaching capacity of thumbs and fingers. Therefore, one-handed interaction is not in the scope of our study.

As a result, with this study we contribute to the field with (1) a user-defined gesture set containing most preferred on-skin gestures specific to hand area, (2) in addition to the most preferred gestures, a set of exclusive gestures specific to this interaction modality, (3) analysis of various characteristics of gestures by creating a taxonomy and analyzing user input over the quantitative subjective evaluation scores, semi-structured interview and mental models, and (4) discussing implications for difference between intuitive and exclusive gestures, design implications and possible application areas.

BACKGROUND AND RELATED WORK

Skin-based input

Skin-based input systems are trending user interface modalities because of the skin's many affordances. Skin is claimed to have benefits such as its availability, accessibility and elasticity [9,14,30]. People work on it intuitively based on years of muscle memory and hand-eye coordination, even though it works reliably without visual feedback [21,42,43]. Instead of an external controlling system, skin-based technologies augment one's own body, creating a direct link between the user and the product [20]. Moreover, compared to the other free-hand modalities like mid-air gestures, these systems can be more precise [9] since touch/non-touch state can be interpreted as the beginning and end points of the gestures which normally created a blurriness in mid-air gesture systems [33]. They can also overcome the problems of getting tired and being socially unacceptable [21,28,36].

Many recent studies from diverse domains work on skin-based gestures as a form of input. Various methods have been developed to track skin touch which work by optical sensors [6,13,16], auditory sensors [14], electrical capacity [3,35], and magnetic sensing [4]. These studies present a large selection of application that realizes skin-to-skin input for device control, yet they do not guide the field about the skin-gestures preferable by users in terms of design specifications.

Still, several research indicated the user preferences for skin-gestures for specific parts of the body without being exposed to technical restrictions. Some of skin-based systems work on the whole body [21]. However, since touching various points on the body is not efficient and socially awkward in public settings, many studies have turned to the arm or the forearm as their input surface. Arms provide a reachable surface for the users as they are less likely to be covered by clothes compared to other body parts [43]. For example, [43] have found that when asked to perform a gesture anywhere on the arm, participants performed 50% of the gestures on the forearm and 44% on the hand area. However, we believe that the whole arm is still too broad for an efficient use since it lacks privacy and requires larger movements than conventional methods of interaction with electronics.

This selection of previous work shows that there are plenty of studies conducted on skin input. It is proved to be a usable and well-received modality by many users across different domains. Studies also investigate users' preferences and behavior regarding skin-based gestures. However, most of these studies use a large input surface and there is a gap in the field on the matter of hand-focused gestures.

Hand-focused gestures

Among other body parts, hands are particularly important for gestural interaction. First, hands enable various poses and gestures provided by numerous knuckles, resulting in a fruitful input set [1,7,34] and much effort has been put on hand posture detection [10,40,48]. Hands also provide a precise tracking for sensors as [42] have shown by developing a tracking system which can detect touch to inner palm with 1 mm error. [6] showed that users can detect 9 different areas of the inner palm eyes-free and easily interact with the surface. This indicates a high level of proprioception around the hand area resulting in increased usability. Hands are also unlikely to be covered by clothes, which makes them the most available and accessible skin surface on the body. Moreover, gestures performed by hands/palms are more acceptable in social environments [17,38], since they require minimal movement and can be concealed.

Parallel with above information, many studies were conducted on on-skin gestures focusing on the hand area. [6] created a palm-based interaction system for eyes-free TV remote controlling. [42] developed a system which recognize gestures drawn to the palm area. [11] implemented a palm-based imaginary interface and collected user data suggesting that palm-based interfaces are usable without visual cues. [38] generated a gesture-set and taxonomy for hand-skin interaction, yet it is done in a comparison context with other modalities and only for gaming scenario. These studies show that, much effort has been put into implementing and understanding the use of hand-specific on-skin gestures. However, user-preferences for this type of modality were not investigated by a focused study and for casual/daily interactions with electronic devices.

METHOD

For understanding the user preferences on HSoS gestures, we conducted a user-elicitation study. Guessability studies based on user-elicitation give voice to users' preferences and provide a user-centered design setting. Developers and designers often underestimate the needs and the preferences of end-users regarding gestures while developing gestural interfaces. A mismatch between designers' and users' mental models for the input gestures can result in a gulf of execution [27]. User-elicitation involves presenting users with tasks (referents) asking them to create gestures to accomplish these [45]. This method has proven beneficial for different types of novel systems across many studies [22,32,36,37,39,43]. Giving voice to users in the production process yields many benefits as it increases usability and provides designers with a solid ground where they base their inspirations for future work. Furthermore, these kinds of user-defined gesture sets resulted in increased memorability and likability, compared to designer-made gestures, even by users who have seen the gestures for the first time [25].

No	*Task name*	*No*	*Task name*	*No*	*Task name*
1	Select	10	Previous	19	Emergency call
2	Navigate	11	Switch task	20	Increase volume
3	Open	12	Scroll up	21	Decrease vol.
4	Minimize	13	Scroll down	22	Shuffle
5	Maximize	14	Accept	23	Play
6	Close	15	Reject	24	Pause
7	Zoom in	16	Accept call	25	Rewind
8	Zoom out	17	Reject call	26	Forward
9	Next	18	Mute		

Table 1: List of the tasks

Participants

A total of 19 undergraduate students took part in the study (M_{age}= 21,2, SD=3,1, 9 Females, 10 Males). All participants reported frequent use of computers and smartphones in daily life, so they were familiar with touch as a form of input.

Materials

21" size screen was used as a display for showing tasks. Gestures were recorded by Logitech C270 Webcam HD with 640x480 resolution that was placed to capture the upper body of the participant. This process was completed by an experiment and an analysis tool, which we developed and named GestAnalytics [2], to standardize the process and decrease human error factor (Figure 1 and 2).

Procedure

Participants were welcomed to the setting by the researcher and they signed the informed consent form. They were informed about the process and were asked to perform *two-hand gestures that involve skin-to-skin touch* for each video clip they saw, and then they filled the subjective evaluation questions for each gesture.

As the process began, the software we developed first asked the participant to (1) fill in demographic information, then

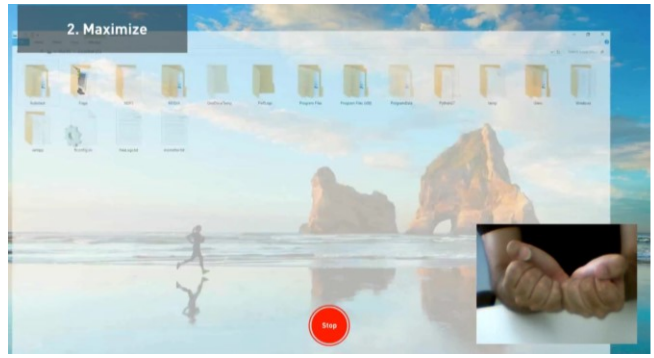

Figure 1:Recording of a gesture video for Maximize task

(2) presented a short clip of the task (e.g. a browser window maximizing as in Figure 1) with the command appeared in verbal form on the top of the screen (e.g. "Maximize"), (3) started recording with the participant's cue, (4) recorded as the participant performed their preferred gesture and (5) stopped afterwards, (6) presented subjective evaluation questions (Table 2) after the gesture of each of task [36], and (7) presented the clip of the following action when the participant clicked next. All 26 tasks (Table 1) were in randomized order for each participant (These tasks are a modified version of [24] by filtering the tasks for daily interaction). With this method, participants were able to complete the process with minimal interference from the researchers. The videos of the tasks were shown along with the relevant command name to create a cognitive feeling of completion for the participant. In the beginning, we asked participants not to limit themselves only to desktop or mobile devices albeit demos only showed several types of interfaces.

Following the user-elicitation method discussed earlier, participants were asked to perform skin gestures with two hands that felt natural and intuitive to them to complete the tasks that were shown. At the beginning of the study, they were encouraged to perform different gestures for each task so they would be pushed out of their comfort boxes to create

Item Code	
A (Memorable)	The gesture I have performed was memorable
B (Social) [46]	I can perform this gesture in a social environment without feeling uncomfortable
C (Fitting) [46]	The gesture I have performed was fit the for the task
D (Tiring) [36]	The gesture I have performed was tiring

Table 2. 7 Point Likert Scale Subjective Evaluation Items

variation, but same gestures were accepted when participants wanted to perform it again for different tasks. There was no limitation to the types of gestures they performed, with the only mandatory condition being skin-to-skin touch. Think aloud procedure was also applied to obtain rich qualitative data, where participants were asked to verbally describe which movements they were making and why they chose that specific gesture. At the end of this production process, we obtained the "*intuitive gesture set*".

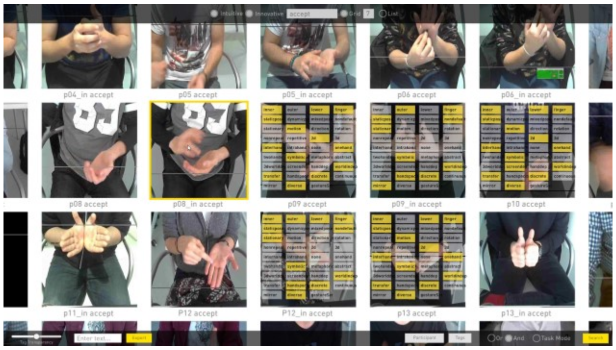

Figure 2: Analysis tool for participant gesture videos

After this phase, the second phase began with an identical process. The only difference was that participants were asked to perform more creative gestures. They were explained that some of the gestures they performed earlier were actually transfers from existing user interfaces like multi-touch screens; thus this time they were requested to avoid this and use their hands in more innovative ways that benefit the hand properties like hand posture, finger positions and skin elasticity. They were told that they could perform the same gesture they produced in the first phase if they believed it follows this rule. Based on the second phase, we obtained the "*exclusive gesture set*". Finally, researcher carried out a short semi-structured interview with the participants focusing on their attitudes towards this kind of a controlling system and scenarios or contexts where this system could be preferred over classic ones. In total, the two phases and the interview took approximately 50 minutes.

Coding and Analysis

Taxonomy

Firstly, a new system of taxonomy for classifying gestures was created. With this taxonomy, we aimed to categorize gestures according to various features and wanted to acquire a quantitative record of the characteristics of HSoS. Later, another software for better analyzing the data was developed. As seen in Figure 2, all gestures belonging to a single task can be seen in one window enabling the researcher to identify patterns and differences within a task easily. All participants' video clips for the related task play simultaneously, so one can either focus on one single user's suggested gesture or overview all suggested gestures for one task at once. Moreover, one can tag each video with different keywords, in our case with taxonomy elements. This way, all gestures were examined according to our taxonomy and tagged one by one. A total of 988 gestures were collected, yet 43 of them were dropped from analysis due to the corrupted recording or lacking of skin-to-skin contact in the performed gesture. One experimenter who is experienced in gesture coding and another trained coder coded the data. 20% of the data was coded by both coders with 81% agreement; conflicts were discussed and dissolved as done in the literature [5].

Agreement

Agreement score (*A)* among all suggested gestures for each task was calculated based on the following formula [45]:

$$A = \frac{\sum_{t \in T} \sum_{Pi \subseteq Pt} \left(\frac{|Pi|}{|Pt|} \right)^2}{|T|}$$

In Eq. 1, t represents a task in the set of all tasks T, P_t is the set of proposed input actions for task t, and P_i is a subset of identical input actions from P_t. The range for A is $[|Pt|^{-1}, 1]$.

The agreement scores were calculated separately for intuitive and exclusive gestures. Since intuitive gestures were performed in the first phase and were the first choice of participants, we expected them to feel natural and thus agreement scores for intuitive gestures to be higher compared to exclusive gestures' scores. An important part of calculating agreement score is the identification of similar gestures within the set of all proposed gestures for each task. We marked gestures which were identical, very similar with minor differences or shared similar mental models as "similar" gestures. The gesture which had the highest count among all gestures was selected for the final user-defined gesture set. For example, during the second phase opening joined hands like book had a count of 6 over 19 gestures for *open* task so it went into the *exclusive gesture set.*

Subjective Evaluation

We ran paired sample t-tests on the means of subjective evaluation scores to get an idea of what participants felt about the gestures they proposed. These scores were used to determine the most liked and disliked gestures, examine the differences between intuitive and exclusive gesture sets and were evaluated along with other results to see if they yielded any correlations.

RESULTS

Taxonomy

There are several types of gesture classifications in the field, but we did not encounter one directly related to HSoS gestures. [46] created a taxonomy for surface gestures examining characteristics like hand pose, movement and gesture location. We followed a similar method where the main skeleton of the taxonomy was inspired by Wobbrock et al.'s surface gestures taxonomy [46], but we further involved considerably more and some revised categories since our study extends beyond surface gestures. Composing this taxonomy was a process of repeated examination of the data and extensive discussions among the authors. Every time one of the facets failed to exhaustively cover an aspect of a gesture, new terminology was created to include these aspects. By creating this new categorization system, we aimed to achieve a new arrangement where HSoS gestures can be analyzed thoroughly.

Hand posture category refers to the condition of the hand while performing the gesture. "Surface" subcategory indicates which surfaces of the hand are involved in the skin touch. "Pose" refers to the hands' shape and is based on [37]'s *Form* category. In this group, *default pose* refers to situations where hands are either held flat or one hand is flat

Hand Posture	Surface	Inner	Touch on the hand's inner surface
		Outer	Touch on the hand's outer surface
		Lower	Touch on the lower area; palm/back of the palm
		Upper	Touch on the upper area; fingers
	Pose	Static Pose	Pose held same during gesture for both hands
		Dynamic Pose	Pose changes during gesture for both
		Mixed Pose	One hand static, one hand dynamic
		Default Pose	Flat hand or pointing posture
Hand Action	Movement	Stationary	Hand is stationary in one location in 3D space during gesture
		Motion	Hand changes location during gesture
	Movement Nature	Direction	Movement has deliberate, specific directionality
		Rotation	Rotational movement from the joints
		Non Repeatable	Random movement, not replicable
		Repetitive	Exact movement is repeated to complete task
	Depth	2D	Movement only in x and y axes within its world
		3D	Movement in x, y and z axes within its world (depth)
	Environ ment	Inter Hand	Movement limited to two hands
		Intra Hand	Movement extends to 3D environment around the two hands
	Moving Hands	One Hand	One hand moves
		Two Hands	Both hands move
Nature		Symbolic	Gesture visually depicts a symbol
		Metaphorical	Gesture indicates a metaphor
		Abstract	Gesture- task mapping is arbitrary
Binding		3D World Dependent	Location defined on actual 3D world space
		Screen Dependent	Location within hand defined based on mapping from the screen
		Hand Dependent	Location based on the form of hand
		World ndependent	Location is irrelevant to any factor
Interface		Transfer	Gesture is transferred from existing interface modalities
		Hand Specific	Gesture is specific to human hand interface
Flow		Discrete	Task response occurs after the gesture
		Continuous	Response occurs while gesture is performed
Hand Relation		Mirror	Two hands do the same gesture
		Diverse	Two hands do different gestures

Table 3. Taxonomy Categories and Tags

while the other one uses the index finger as if using a tablet screen. We decided to mark these two specific incidents of posture since they were very common among all gestures. *Hand action* category is based on the movement of the hand. "Movement" subcategory indicates whether hands move in space to perform the gesture. If gesture is *stationary*, no further examination is made within the hand action category. However, if the gesture is in *motion*, we report different characteristics of this movement.

Since these "Movement nature", "Depth", "Environment" and "Moving hands" subcategories are only used for gestures which are *in motion*, it should be kept in mind that their percentages, by design, cannot be equal with elements which are applicable to all gestures. For example, the percentage for *inner* tag could be valid for all 484 intuitive gestures whereas *inter-hand* tag can only be valid among 360 dynamic intuitive gestures. It is also important to note that elements of the "Movement Nature" and "Surface" categories are not mutually exclusive, and therefore one gesture can have multiple tags from those categories.

Nature and *Binding* categories were borrowed from [46]'s taxonomy with minor modifications. *Nature* category refers to the mental origin of the gesture and how the relation between the task and gesture was made. *Binding* indicates whether the location of gesture was deliberate and if so what it depends on. *Interface* refers to whether the gesture was a transfer from other conventional modalities (keyboard, mouse, touchscreen etc.) or can be performed uniquely within this modality. *Flow* is another category borrowed from [46] which marks whether the action is completed by the computer as the gesture is occurring or after it has been completed. This tag was most relevant for tasks like *increase volume* or *scroll up* since the amount of increasing or scrolling depends on the duration of the input in many other interfaces. Finally, *hand relation* signifies whether the two hands were doing the same gesture or not.

We had 484 intuitive gestures at the end. While 124 of these gestures were *stationary*, 360 involved *motion*. Similarly, out of 473 exclusive gestures, 133 were static and 341 involved motion. A breakdown of all taxonomies is shown in Table 4.

Agreement

The user-defined gesture set was one of the main goals of this study. Most preferred gestures for each task is depicted in Figure 4 and the comparison of agreement scores are reported in Figure 3. These sets contain both the intuitive and exclusive most-preferred gestures. We illustrated one gesture for each task in both gestures sets, even when the agreement scores were low since we believe that these demonstrate the mental models of the participants and create inspiring and noteworthy alternatives for each task. As we expected, there was a higher rate of agreement among intuitive gestures (M=0.24, SD=0.16) compared to exclusive gestures (M=0.14, SD=0.04), $t(25)$=3.00, p<.01.

In intuitive gesture set, *scroll down* and *scroll up* tasks had the highest agreement scores among all. This result is not

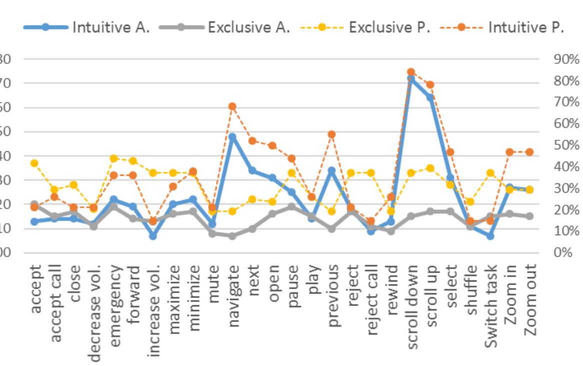

Figure 3: (A) Agreement Scores and (P) Percentages of Gestures in User-Defined Gesture Sets

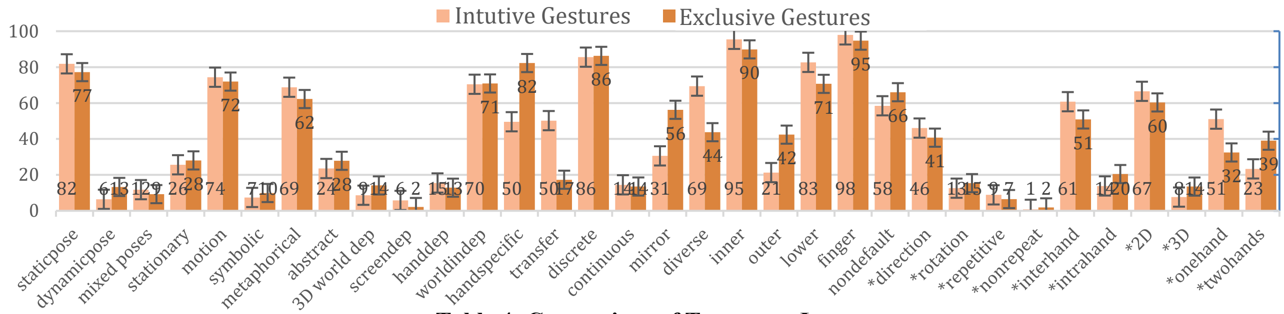

Table 4: Comparison of Taxonomy Items

surprising since scrolling is a widely-used task either in desktop computers or mobile devices. *Increase/decrease volume, mute, shuffle* and *switch task* were those among the lowest agreement scores. These tasks are either not frequently used compared to the scrolling or they have different command sets (e.g. switch task is alt-tab for Windows OS while it is double pressing the home button for iOS). Therefore, they did not evoke a clear memory for participants. *Accept*, *pause* and *emergency call* had the highest scores among exclusive gestures. *Accept's* agreement score was even higher than its counterpart in the intuitive set. Similarly, *switch task* also has a higher score than the intuitive one. Moreover, *accept call, close, emergency call, increase volume, play, reject, reject call* and *shuffle* tasks have similar agreement scores with intuitive gestures. All of these gestures do not carry a clear gesture memory from existing interfaces or a visual correspondent when compared to some other tasks like zooming or scrolling. Therefore, we can state that exclusive gestures can be alternatives especially to tasks that do not have a strong gesture memory or depend on visual cues such as accept, reject, shuffle, play etc. Moreover, the case of *Switch task* and *accept* may show that during the study participants were so much accustomed to transferring from existing modalities, they were not able to think of a gesture that can be more suitable or even intuitive for the action.

The resulting user-defined intuitive gesture set contains 186 of 484 suggested intuitive gestures, culminating a 38.43% coverage of all suggestions. Exclusive gesture set contains 130 of 473 suggested gestures, covering 27.48% of all.

Subjective Evaluation

As expected, intuitive gestures had higher mean scores for items A (Memorable), B (Social) and C (Fitting) than exclusive gestures. This difference was significant for items A, $t(25)=5.18$, $p<.0001$; for B, $t(25)=7.75$, $p<.0001$, and C, $t(25)=2.08$, $p<.05$. We expected this result since intuitive gestures were mostly transferred from the interfaces that participants were used to use. Therefore, the gestures proposed by the users were naturally easier to remember, feel less awkward to perform in social environments and better corresponded to the tasks. The comparison of average subjective evaluation scores for each task is in Table 5.

A remarkable result of subjective evaluation was that exclusive gestures were perceived as less tiring than intuitive gestures. Item D (tiring) had significantly lower scores for exclusive gestures than intuitive ones $t(25)=3.33$, $p<.001$. This result is also visible from the exclusive gesture set. Overall, the exclusive gesture set has 13 gestures with the *stationary* tag while the intuitive set only has 5. Furthermore, we observe less directional gestures in exclusive set which may suggest the motion in these gestures are more minimal or subtle as in *open* gesture. Therefore, we can state that although gestures proposed in the intuitive set may be easier to get used to, it does not always mean that they are more usable. The unique characteristics of hands to form different poses create opportunity to express tasks with less motion.

After evaluation scores were determined, we ran correlations between evaluation scores and agreement scores for each task. Although there were some individual tasks showing clear preference based on their high ranks in both agreement scores and subjective evaluations as mentioned above, we only found a significant relation for item A in intuitive gestures, $t(24)=0.47$, $p<.05$. For all other items in both gesture types, there were no significant correlations. It should be kept in mind that this evaluation only gives idea about the perception of the users and should be elaborated with further studies in actual use-case scenarios.

	Intuitive				Exclusive			
Task Name	***A***	***B***	***C***	***D***	***A***	***B***	***C***	***D***
accept	6,37	6,21	6,00	2,05	6,37	6,16	5,84	1,47
accept call	6,42	6,58	6,00	1,63	6,00	5,95	5,68	1,53
close	6,32	6,58	6,11	1,95	6,00	6,26	5,58	1,58
decrease v.	6,37	6,42	5,79	1,79	6,11	6,11	5,47	1,68
emergency	5,74	6,21	3,74	1,79	6,05	6,26	4,84	1,74
forward	6,26	6,58	5,79	1,74	6,00	6,16	5,79	1,58
increase v.	6,42	6,37	5,84	1,63	6,32	6,26	5,79	1,63
maximize	6,37	6,42	5,68	1,89	6,26	6,26	5,74	1,63
minimize	5,89	6,32	5,11	1,68	5,89	6,16	5,63	1,63
mute	5,84	6,32	4,79	1,74	5,63	6,21	5,16	1,53
navigate	6,58	6,58	5,63	1,79	6,11	5,95	5,53	2,05
next	6,58	6,74	6,32	1,74	6,26	6,37	5,68	1,63
open	6,21	6,11	5,89	1,63	6,05	5,95	5,68	1,89
pause	6,37	6,53	5,68	1,53	6,42	6,37	5,79	1,47
play	6,05	6,53	5,26	1,68	6,26	6,00	4,95	1,53
previous	6,58	6,42	5,84	1,89	6,32	6,32	5,95	1,53
reject	6,63	6,58	6,21	1,63	6,37	6,21	5,74	1,37
reject call	6,42	6,42	5,89	1,84	5,95	6,16	5,74	1,63
rewind	6,37	6,42	5,84	1,74	6,00	6,21	5,47	1,63
scroll down	6,53	6,58	6,16	1,58	6,11	6,21	5,89	1,53
scroll up	6,68	6,47	6,53	1,84	6,26	6,21	5,84	1,37
select	6,37	6,53	6,00	1,84	6,11	6,16	5,11	1,58
shuffle	6,16	6,32	6,05	2,11	6,21	5,89	5,89	1,42
switch task	5,79	6,63	5,05	1,84	5,37	5,95	4,79	2,11
zoom in	6,58	6,63	6,11	1,89	6,00	5,84	5,79	1,63
zoom out	6,47	6,58	5,89	1,63	6,05	6,05	5,58	1,74
Mean	**6,32**	**6,46**	**5,74**	**1,77**	**6,10**	**6,14**	**5,57**	**1,62**
SD	*0,26*	*0,15*	*0,57*	*0,14*	*0,23*	*0,15*	*0,33*	*0,18*

Table 5: Average subjective evaluation scores for each task

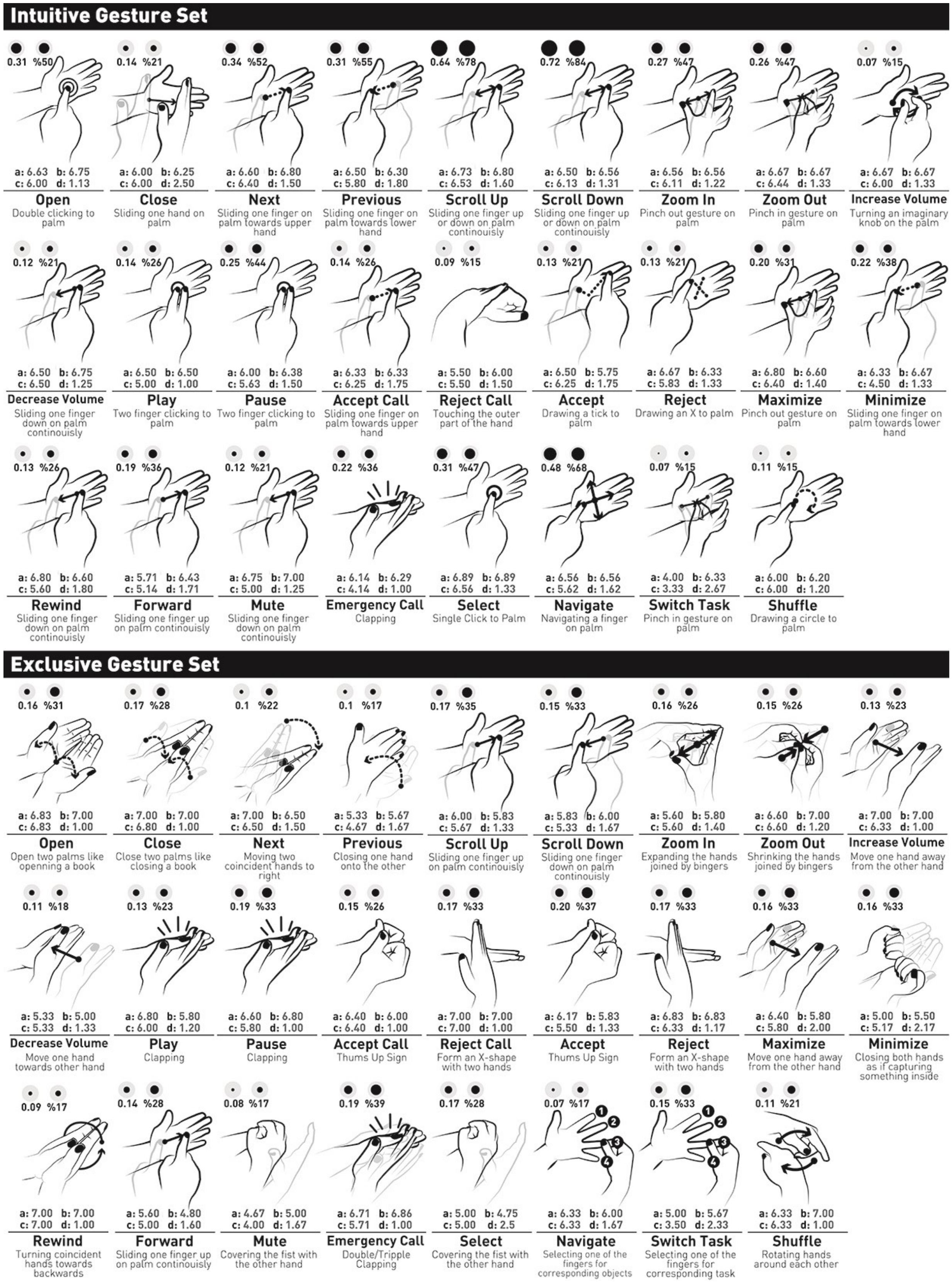

Figure 4: Intuitive and Exclusive Gesture Sets. (a,b,c and d refers to A (memorable), B (social), C (fitting), D (tiring) orders respectively. Dots in the left corner of each gesture represent agreement score and percentage respectively. Dashed Line: Discrete Motion, Continuous Line: Continuous Motion)

The means were also calculated specifically for gestures in the gesture sets. For the gesture sets, the significant difference between intuitive and exclusive gestures disappeared for items A, C and D, p>.05. Intuitive gestures still scored higher than exclusive ones in Item B, $t(25)=2.18$, p<.05, but since the exclusive gestures are uncommon to perform in social environment, this is expected. This lack of difference between two gesture types shows that for those gestures that people agreed upon, the level of fitness is the same and exclusive gestures in the set are just as usable as intuitive ones. Still, in Figure 4, the total number of gestures in the average calculation differs for each gesture. Therefore, this information only gives idea about the users' disposition towards that specific gesture, not for comparing gestures.

Semi-Structured Interview

Five participants saw the remote controlling opportunity without mediator device as the biggest advantage. They claimed that it would be especially beneficial in home environment where electronics around the house can be easily controlled from a single point. They also believed this interface is fast and efficient since one directly interacts with their own body, which makes it practical and accessible.

Participants' biggest concern was that the obligation to use two hands was *limiting*, where in some tasks one hand would be sufficient. Although item A (memorability) had an average of 6.21 out of 7, three participants believed that the gesture set necessary to use the system would be hard to memorize and this could cause user-related problems. A conceptual interface with all 26 tasks may have overwhelmed the users in that case, and in more simple systems with fewer tasks memorability may not be an issue. Last concern reported by three participants was that using the system in public could be awkward since outside observers would not immediately be able to understand that the user is engaged with an unseen device. However, the overall mean of item B (social) was 6.3, pointing to almost complete agreement with gestures' social acceptability. These participants may have answered this question considering gestures performed poor in Item B.

Overall, participants were excited to try a new type of interaction and reacted positively to being involved in the production process of a new system. They believed such an interface could allow multitasking where one has their hands dirty or while driving. Other than home use, contexts such as gaming, disabled users and teachers in the class environment were introduced by participants as potential areas of use.

Mental Model Observations

Although there is plenty of quantitative data regarding different characteristics of user-defined gestures, an examination of underlying mental patterns of participants is necessary to understand and interpret the numbers. Some of our most salient observations are already noted by previous work in their analysis of mental models based on think-aloud data [24,43]. The most explicit one was that participants frequently fell back onto touchscreen gestures that were readily available in mind. Tasks which do not possess a popularly recognized gesture scheme such as *reject call, pause* and *emergency call* yielded more hand-specific gestures as participants were compelled to create more innovative ones. Moreover, we observed that taxonomy item *transfer* decreased in exclusive gestures while *hand specific* item showed a significant superiority. This indicates that the second phase of the study worked for yielding gesture types which can be unique only to this modality as expected. An expected but still a prevalent case was the use of reversible gestures for reversible actions. Tasks such as *zoom in/out, scroll up/down* were almost always the exact replications of their opposites, with only the direction of movement changing. The rest of our observations are our novel contributions to the field.

Part of the Hand is a Factor

Different surfaces of the hand held different meanings for the participants. We observed that the inner palm was seen as the "main" surface to base gestures upon. Some participants pushed their calls "away" from their palms for *reject call* by swiping their whole hand over the palm, therefore excluding it out of the hand. A similar case is the outer surface of the hand which is often associated with "negative" actions. *Reject call* is a good example where participants tapped on the outer surface of the hand because it was the "other" area. P5 reports, "*It is the back of my hand, so it is a refusal movement*" as he taps on the outer fist. Use of fingers was also notable. Although the index finger is mostly used for pointing, when the metaphor of fragmentation was needed, finger area was the preferred choice because of their separated form. This was most salient in *switch task* where different fingers had different programs assigned to them which would be opened when the finger is selected.

One Hand as Reference Point/Object/Surface

One of the hands was often used as the reference point or the touch surface. For example, in *increase volume* from the exclusive set, one flat hand was still while the other flat hand would move away from it, and the distance between the two would represent the increased volume. For touchscreen-transfer gestures, they would hold one of their hands flat and worked on it with the other hand as if using a multi-touch screen. Therefore, most of intuitive gestures involved the movement of only one hand whereas the use of two hands increased for the exclusive gestures. When they were forced not to use the touchscreen anymore, the second hand became more active and the use of 3D space surrounding the hands increased, as can be observed in *3D world dependent, 3D, non-default pose* and *twohands* of the taxonomy.

Hands also transformed into many different objects from daily life. For example, for the task *mute*, P7 suggested a gesture where one fist became a speaker and the other hand covered it as if shutting its sound down. *Switch task* and *select* from exclusive set and *increase volume* and *reject call* from intuitive set are examples for this tendency. These gestures show that hand is easily imagined as a more customary object when users are faced with more abstract versions of similar tasks they perform in daily life.

Behavior Observations

We reported the common behaviors and characteristics that we observed even if these were not verbally expressed by participants in think aloud process.

Become the Interface

When participants were instructed not to use the touchscreen metaphor anymore in exclusive gestures, they often tried to create an interface or feedback system of their own. In intuitive gestures, they imagined the flat hand as the customary touchscreen. However, with exclusive gestures, they were forced out of this comfort zone and the habitual imagined feedback was gone, so their gestures became more physically present and contained more spatiality. For example, *open* was a single click for intuitive gestures, but it was opening two flat hands as if opening a book for the exclusive gestures, which was a more visible gesture and defined in starting and ending points. Similarly, P09 triple tapped his palm for *emergency* in intuitive gestures but made his hands into a wing shape for the exclusive gesture, using the metaphor of a helper angel. We believe participants could not rely on simpler gestures anymore when they lost the advantage of past experience, so they created gestures that were more well-defined and give feedback signaling the completion of the task. *Open, close, mute, minimize, switch task in* exclusive set can be examples of gestures which provide self-feedback. We can also observe this as gestures with *dynamic pose*, *3D world dependent, non-default pose* tags increase in exclusive set.

Unsophisticated Use of Skin

Most of the gestures involved movements such as clapping, clicking or dragging fingers along the hand surface which are quite habitual movements in daily life, outside of any electronic context. Contrary to a previous study which focused on skin-gestures in arm area [43], participants did not prefer using rather complicated actions such as pinching or twisting the skin or using the fingernails for their gestures although we had highlighted the skin properties of hand during gesture elicitation process. This indicates that although exclusive gestures differed from intuitive ones in terms of the space they occupy, the amount of movement and different hand postures; the use of the skin and the hand surface remained simple and unsophisticated for both gesture types. This may have originated from the fact that when hands were involved, the manipulation opportunity for posture, movement availability in 3D environment or use of different areas like finger zone, palm and outer hand overcame the preferences for skin-manipulation in gestures.

DISCUSSION

Our findings about reversible and transfer gestures, and agreement score averages corroborate with Weigel's study [43] which similar to ours in terms of methodology. However, while results of [43] mostly elaborate on upper arm and skin properties like elasticity, our work specifically focuses on hand area. Our results, contrary to [43], suggest that skin use was not common and other hand properties were more frequently used. As a result, their final gesture set has 3 hand-specific gestures whereas all of our gesture set consists of hand-specific ones. Thus, different from [43] our results interest research like [6,8,11,42] directly while [43] focuses to a wider part of the body. We further present exclusive gestures by comparing to the intuitive ones, obtaining remarkable results such as exclusive gestures being perceived less tiring than the intuitive ones. We also present a 33-element taxonomy quantifying the characteristics of hand use that may be useful for also other hand related studies like [19,31].

Intuitive and Exclusive Gestures

Legacy bias is an inevitable part of creating novel interaction techniques, and our findings indicate that participants often fall back onto habitual gestures in order to avoid mental and physical demand [23]. They do not only produce conventional gestures, but also believe those are fitter to the related tasks than the exclusive gestures. Still, we can observe that most of the gestures are almost identical in intuitive gesture set like *volume, scrolling, next, previous, forward* and *rewind*. Therefore, these gestures can be used without confusion only when one of these functions present. A system that has availability to play a video and manipulate the volume of the sound at the same time would not be able to benefit from the intuitive gesture set. Therefore, although agreement scores and percentages are mostly lower, exclusive gesture set forms a favorable alternative to intuitive gesture set. Moreover, it also shows similar agreement scores between tasks that are abstract in nature and do not have a strong gesture memory.

Other than that, exclusive gesture set can be more favorable in use-cases where a visual interface is not available since most of these gestures have meanings independent from the visual context. For example, *open* gesture represents a book and when it is open, user can understand the opening action is completed without seeing it on a display.

Design and Development Implications

Our observations suggest that hands can be perceived as interface elements by participants. In the intuitive gesture set, one hand usually replaced the actual screen and participants performed gestures on one of their palms. The exclusive gesture set yielded similar results, yet hands were considered as various objects instead of screens. For example, it became a speaker in *mute* task where the user covered it to prevent sound spreading. In this direction, we suggest designers to make use of hands' capability of transforming and being perceived as different objects.

Furthermore, hand is perceived as a segmented interface. Participants perceived outer part of the hand as negative and dedicated it to negative actions like rejecting an incoming phone call. Fingers, inspired by their form, are considered as segmented interface elements like tabs. Moreover, palm is recognized as an area to keep things in, other than a control surface. Therefore, while designing gestures for such interfaces designers should mind the different parts of the hands so they can assign gestures which require less movement and still be in parallel with users' minds.

In terms of the development, we classified requirements for our gesture sets as *detection of relative hand positions, posture detection, rotational and directional movement and single and multiple finger tracking in palm.* We recommend possible technologies which work towards realizing these aspects. For detecting relative position of hands, millimetric-radar wave sensors [19] can be used. [19] can also detect basic postures like open hand or fist which are sufficient for our gesture set. For finger tracking, [49] proposes a way to include a ring sending AC signals and a wrist-worn bracelet and [42] comes forward with an IR cam and a laser-line projector worn on wrist. With placements on upper or bottom part of the wrist, these can also recognize inner or outer parts of the hand as touch area. Fingers can be tracked with a sonar as in [26] by placing it around the hand. [26] is also speculated to track multi-finger gestures, yet an implementation was not made. Multi-finger tracking is possible with computer vision as in [12], however it is disadvantageous because it requires a stable cam that constantly sees the palm and is liable to low-light conditions. Finally, movement detection can be provided with IMU sensors by placing it to wrist's closer part of the hand. All technologies require wrist, hand or head worn devices. Thus, in daily use, usability of these devices can be a concern, which is beyond the scope of the current study. Other than that, we must indicate that there is not a current sensor fusion system that can realize the proposed gesture sets. However, this area is developing rapidly and a system that can recognize our gesture sets can be developed with the proposed methods.

Possible Application Areas

Participants proposed several application areas for usage of HSoS. Although most of the previous work suggests the usage of skin gestures for mobile devices and smart watches, users favored the usage of this system also for remote controlling of devices like TV, PC or tablet. They also found it useful when they are far away from their mobile devices.

One of the use-cases proposed by participants was using this modality while driving for controlling the radio or other car functions without taking hands off the steering wheel. However, only simple actions like tapping the back of the hand or connecting two hands over the steering wheel can be used. Another context proposed was watching a recipe while cooking. In this case, they expressed that this system may be useful since touching to any device would not be comfortable or hygienic. Participants' speculations indicate that this modality can be useful in conditions where direct contact with the devices is not possible or preferable.

CONCLUSION

In this study, we conducted a detailed analysis on hand-specific on-skin (HSoS) gestures preferred by users. With the user-elicitation method, we created a 33-element taxonomy and analyzed gestures based on the subjective evaluation and the semi-structured interview data of the users. Upon these, for the very first time we developed two user-defined HSoS gesture sets with gestures referring to various qualities of hands. While one of these is based on users' natural preferences, the other one has the potential to inspire designers to create more innovative interaction techniques while still staying loyal to users' expectations.

Among all results regarding to underlying mental models of users and insights to negative and positive sides of such interface, we put forth that users found exclusive gestures less tiring than the intuitive ones, indicating that hand-specific interface designers and developers should look for the systems which should detect not only the directional movements of the hands but the 3D motion, different postures or interaction with different parts of the hand.

We believe that HSoS gestures is a promising way for skin interaction and our data is inspiring for both designers and developers. Benefiting from the amorphous form of hands and many potential postures, unexplored areas other than the palm can be integrated into gesture design with increased usability. Moreover, compared to previous work, interaction and interface designers can benefit from the exclusive gesture set which provides a better understanding for novel gestures that can only performed be within this modality.

LIMITATIONS AND FUTURE WORK

The study was conducted while participants were seated. Sitting may have primed the participants towards inertia which resulted in smaller actions. They may have produced more physically demanding gestures if they stood freely and this can be tested in future studies.

All participants were university students who have extensive experience with touchscreen devices. An older generation who does not share touch-screen habits may result in a decreased proportion of transfer gestures from conventional modalities. Still, we observed some participants transferring gestures from old-fashioned phones or binoculars. Thus, an older generation could hold habits which will still result in transfer gestures, only from older types of devices.

This study was conducted in Turkey with Koç university students. Since social norms are highly influenced by culture, social acceptability is open to change under different contexts. Although our findings are mostly congruent with previous work, replicating the study in various other cultures may result in differences in social perception of gestures.

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