Touch+Finger: Extending Touch-Based User Interface Capabilities with "Idle" Finger Gestures in the Air

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ABSTRACT
In this paper, we present Touch+Finger, a new interaction technique that augments touch input with multi-finger gestures for rich and expressive interaction. The main idea is that while one finger is engaged in a touch event, a user can leverage the remaining fingers, the "idle" fingers, to perform a variety of hand poses or in-air gestures to extend touch-based user interface capabilities. To fully understand the use of these idle fingers, we constructed a design space based on conventional touch gestures (i.e., single- and multi-touch gestures) and interaction period (i.e., before and during touch). Considering the design space, we investigated the possible movement of the idle fingers and developed a total of 20 Touch+Finger gestures. Using ring-like devices to track the motion of the idle fingers in the air, we evaluated the Touch+Finger gestures on both recognition accuracy and ease of use. They were classified with a recognition accuracy of over 99% and received positive and negative comments from 8 participants. We suggested 8 interaction techniques with Touch+Finger gestures that demonstrate extended touch-based user interface capabilities.

Author Keywords
Touch input; gestural interaction; interaction techniques, wearable rings; joint interaction.

INTRODUCTION
Human fingers are remarkably dexterous, making touch-based user interfaces an intuitive and effective mode of primary input. Researchers and interaction designers have utilized the fingers to provide diverse touch interaction techniques, for example using touch duration (e.g., long-press), multiple touch points (e.g., multi-touch gestures [7, 32]), and/or different types of finger input (e.g., thumb's contact size [2] and different parts of a finger [11]) for a richer touch input vocabulary. However, the limited interaction space provided by two-dimensional (2D) touch interfaces falls significantly short of the rich gestural capabilities of human fingers.

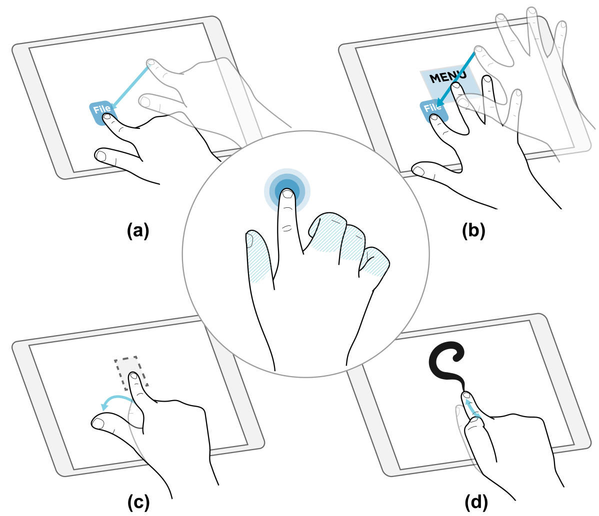

Figure 1. (Center) When one *primary* finger is engaged in touch interaction, the rest of the *secondary* "idle" fingers (blue) are still but are able to move. We utilize these idle fingers to perform various hand poses before a touch or in-air gestures during a touch to add modality and expressiveness to the primary touch event: (a) opening a file by tapping with a "Basic" hand pose, (b) opening a context menu of the file by tapping with a "Spread All" hand pose, (c) deleting the touched object with the index finger by flicking with the thumb and (d) drawing a line with the index finger while controlling the width of the brush stroke by swiping up/down with the thumb.

To address this limitation, researchers have proposed techniques for extending input space. Some researchers have investigated possible alternative interaction spaces above [1, 22], around [3, 35], and on the back [26, 34] of the device. This extended space enables a variety of multi-finger gestures beyond the touchscreen, providing far richer user interactions. More recently, others have explored combining touch with hand gestures [18, 23, 27, 33] to offer more expressive in-

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put than either of them alone. For instance, Air+Touch [5] and Ringteraction [9] augment touch events with thumb-based gestures above the screen.

Our work augments touch input with finger gestures in the air. The main idea is that since not all fingers are engaged in a touch event, we can enhance touch interaction by making full use of the rest of the fingers (secondary fingers) when one finger (primary finger) is touching the screen. By leveraging the "idle" fingers, a variety of hand poses, or in-air gestures, can be performed to add modality and expressiveness to the primary touch event. As shown in Figure 1, users can use the idle fingers for different hand poses to specify the function of a forthcoming touch event. For example, (a) the primary touch with a "Basic" hand pose can open a file or (b) the primary touch with a "Spread All" hand pose can open a context menu of the file. In addition, users can perform in-air gestures with their idle fingers to add extra input information to the primary touch interaction. For instance, (c) the touched object with the index finger can be deleted by flicking with the thumb. Users can also (d) draw a line with the index finger while controlling the width of the brush stroke by swiping the side of the index finger with the thumb. In this manner, the use of idle fingers can enrich current touch interaction and extend touch-based user interface capabilities.

In this paper, we present new gestural interaction techniques called Touch+Finger that extend touch-based user interface capabilities by including the secondary fingers. To explore the possibilities of using idle fingers as additional input sources for primary touch interaction, we constructed a design space based on conventional touch gestures (single- and multi-touch) and interaction periods (before and during touch). Based on the design space, we investigated the possible movement of the idle fingers and developed a comprehensive set of Touch+Finger gestures. To evaluate them on both recognition accuracy and ease of use, we built a Touch+Finger prototype to detect touch and in-air gestures. It consisted of two ring-like devices with IMUs (Inertial Measurement Units) attached, a touch-based device, and an external PC for data processing. With our prototype, we measured the recognition accuracy and user rating of Touch+Finger gestures with 8 participants. We concluded by describing a number of interaction techniques that demonstrate the extended interaction capabilities of Touch+Finger gestures.

Our results show that 20 of the proposed Touch+Finger gestures have a high level of accuracy (over 99%). We received both positive and negative feedback on the gestures. Participants found that some Touch+Finger gestures were easy to perform and useful in allowing them to switch between different modes of interaction and add "expressive" interactions along with the primary touch event. Of the 20 proposed Touch+Finger gestures, not all secondary gestures were found to be user-friendly due to physical constraints and users' attention deficits. The ease of performing Touch+Finger gestures and ergonomic issues will be discussed in more detail.

The main contributions of our work are summarized as follows:

- We present the concept of enhancing conventional touch gestures by using the "idle" fingers to add modality and expressivity to primary touch events.
- We explore the possibility of using the "idle" fingers before and during touch interaction to provide additional input information for the touch interaction.
- We propose feasible Touch+Finger gestures from a careful review of ergonomics and the biomechanics of the human hand.
- We present 8 Touch+Finger interaction techniques that extend touch-based user interface capabilities and support more expressive touch interaction.

RELATED WORK

Our work extends touch-based user interface capabilities with "idle" finger gestures. Here we review the literature related to the enhancement of two-dimensional (2D) touch interaction with secondary fingers and to extending the interaction space beyond on-screen interaction. We also consider prior research on the combination of touch and gesture.

2D Touch Interaction with Fingers

Previous works have proposed different methods for extending the input vocabulary on touchscreens to incorporate the full dexterity of the human hand. For instance, the input modality of a touch event can be enhanced by utilizing extra dimensions of a finger. Boring et al. [2] used the thumb's contact radius as additional input modality to switch between input modes. TapSense [11] employs the diverse anatomy of human hand (e.g., tip, knuckle, and pad) to provide different interaction modes. Finger orientations [29, 30] have also been used as an additional input parameter for touch. Furthermore, there have been a number of research efforts to enhance touch interaction using multiple fingers. Westerman et. al. [32] proposed multi-touch gestures on a 2D screen, allowing users to achieve fine levels of control. In recent years, multi-touch interaction techniques have been improved with recognition technologies such as individual finger identification [6, 19, 29] and whole-hand gesture recognition [8, 21]. However, the limited interaction space of 2D touch user interfaces falls significantly short of the rich gestural capabilities of human fingers.

Beyond On-Screen Interaction

To address the limitations of the 2D touch interaction space, researchers have investigated possible alternative interaction space above, around, and on the back of the devices. SideSight [3] provides virtual, multi-touch interactions around the body of a small mobile device, using infrared (IR) proximity sensors. SideSwipe [35] also leverages the unmodified global system for mobile communication (GSM) signal to enable in-air hand gestures above and at the side of a mobile device. Arefin Shimon et. al., [1] explored hand gestures above a smartwatch in order to overcome the limited interaction space of the small screen. More recently, hovering interactions above the screen [12] have been found to allow for richer and more expressive interactions by identifying the user's intention before a touch event occurs. Much research has been conducted on using the back of a mobile device [26] or handheld device [34] as a possible input space. This extended space enables a variety of multi-finger gestures beyond the touchscreen, providing far richer interactions. However, expanding the interaction space beyond the touchscreen may sacrifice some of the benefits of direct-touch interactions (e.g., increased time for selecting a target and better performance in pointing tasks [16]). Therefore, we seek to combine touch and in-air gestures to maximize the benefits of modality and expressivity.

Combining Touch and Gestures

More recent works have addressed the combination of touch and gestures in order to provide more expressive interactions. Marguardt et al. [22] proposed a unification of touch and gestures called the "continuous interaction space" on a digital surface. Also, TouchID [23] led to novel and expressive tabletop interaction techniques by identifying which hand and which part of the hand was touching the surface, as well as what posture and what gesture was being enacted with the fiduciary-tagged glove. Similarly, Finger-Aware Shortcuts [36] employed finger, hand, and posture identification for keyboards to provide shortcut availability and expressivity. In this system, a key press can have multiple command mappings depending on which fingers and postures were used to press a key. Jackson et. al. [15] also extend multi-touch interfaces by using a combination of multi-touch gestures and 3D movements of the hand(s) above the surface. Furthermore, Kim et al. [18] and Song et al. [27] augmented touch events on mobile devices with finger gestures by using both hands. One hand controls a touch device, while the other hand performs gestures as an additional input. Conversely, Hinckley et. al. [13] explored interaction techniques with one hand for hand-held devices that leverage the combination of touch and motion, suggesting hybrid touch+motion gestures. In addition, Expressy [33], using only one hand, employed the movement of the wrist to add expressiveness to touch-based interactions. Air+Touch [5] focused on in-air gestures performed only with the thumb to enhance touch interaction while the same hand grasped the phone. Also, by using thumb-based touch gestures on capacitive touch sensors in a ring-like device, Ringteraction [9] presented thumb-index touch interaction, which allowed for enhanced input modalities on handheld devices.

Our work relates closely to Finger-Aware Shortcuts [36], in that it also employed the rest of the "idle" fingers to increase the input space. Nonetheless, we focus on touch-based devices rather than the keyboard. To the best of our knowledge, we are unaware of any existing work that enhances primary touch interaction by making full use of these "idle" fingers. Unlike previous work [5, 9], which only focused on thumb-based gesture interaction techniques, our work has focused on exploring different input capabilities of the rest of the fingers to perform hand poses or in-air gestures as additional input for primary touch interaction. Our main focus is to investigate a variety of hand poses and in-air gestures performed by all secondary fingers, and to allow them to extend touch-based user interface capabilities, providing users with a richer input vocabulary for novel interaction.

DESIGN SPACE

The fundamental idea of the design space is to allow idle fingers, in various ways, to enhance conventional touch interactions. Based on prior work on touch gesture techniques [7, 32] and touch interaction periods [5, 33], the two main factors we considered in our design space were touch gesture and interaction period.

Touch Gesture

We aimed to augment existing 2D touch gestures by allowing secondary idle fingers to perform various gestures in the air. We have divided the touch gestures into two categories: Single-Touch and Multi-Touch.

- Single-Touch: This refers to the cases in which one primary finger touches the screen. Based on the movement of the primary finger, users can perform static or dynamic single-touch gestures such as tap (static) or drag (dynamic) on the screen. Our work will explore how secondary fingers can enhance single-touch gestures performed with a primary finger, in this case the index finger. Here, the secondary fingers are the thumb and the middle+ fingers. Middle+ refers to the motion of the middle, ring, and little fingers altogether, due to the anatomy of the human hand (i.e., inter-finger dependencies [28]).

- Multi-Touch: This refers to cases in which two or more primary fingers touch the screen simultaneously. As mentioned above, multi-touch gestures can be also static (e.g., a two-point touch) or dynamic (e.g., pinch and spread). We will investigate how secondary fingers, in this case the middle+ fingers, can enhance multi-touch gestures performed by the primary fingers, in this case the thumb and index finger.

Interaction Period

Based on Wilkinson's conceptual model [33], we have divided touch interaction periods into two dimensions: Before Touch and During Touch.

- Before Touch: This is the period just before the primary finger touches the screen. In this case, the secondary idle fingers can be used to supply additional information to enhance a forthcoming touch by making a variety of hand poses. This allows the touch event to have different input commands depending on the different hand poses.

- During Touch: This refers to the time when the primary finger is touching the screen. In this period, in-air gestures performed with the secondary idle fingers enhance the primary touch interaction by allowing the input of additional commands without interruption.

By combining these two factors, we created a 2×2 design space covering a variety of interaction techniques that leverage the availability of both primary and secondary fingers (Figure 2). Based on this design space, we explore possible Touch+Finger gestures that are ergonomically feasible to users, evaluate them on both recognition accuracy and user feedback on ease of performance, and demonstrate several examples of Touch+Finger interaction techniques.

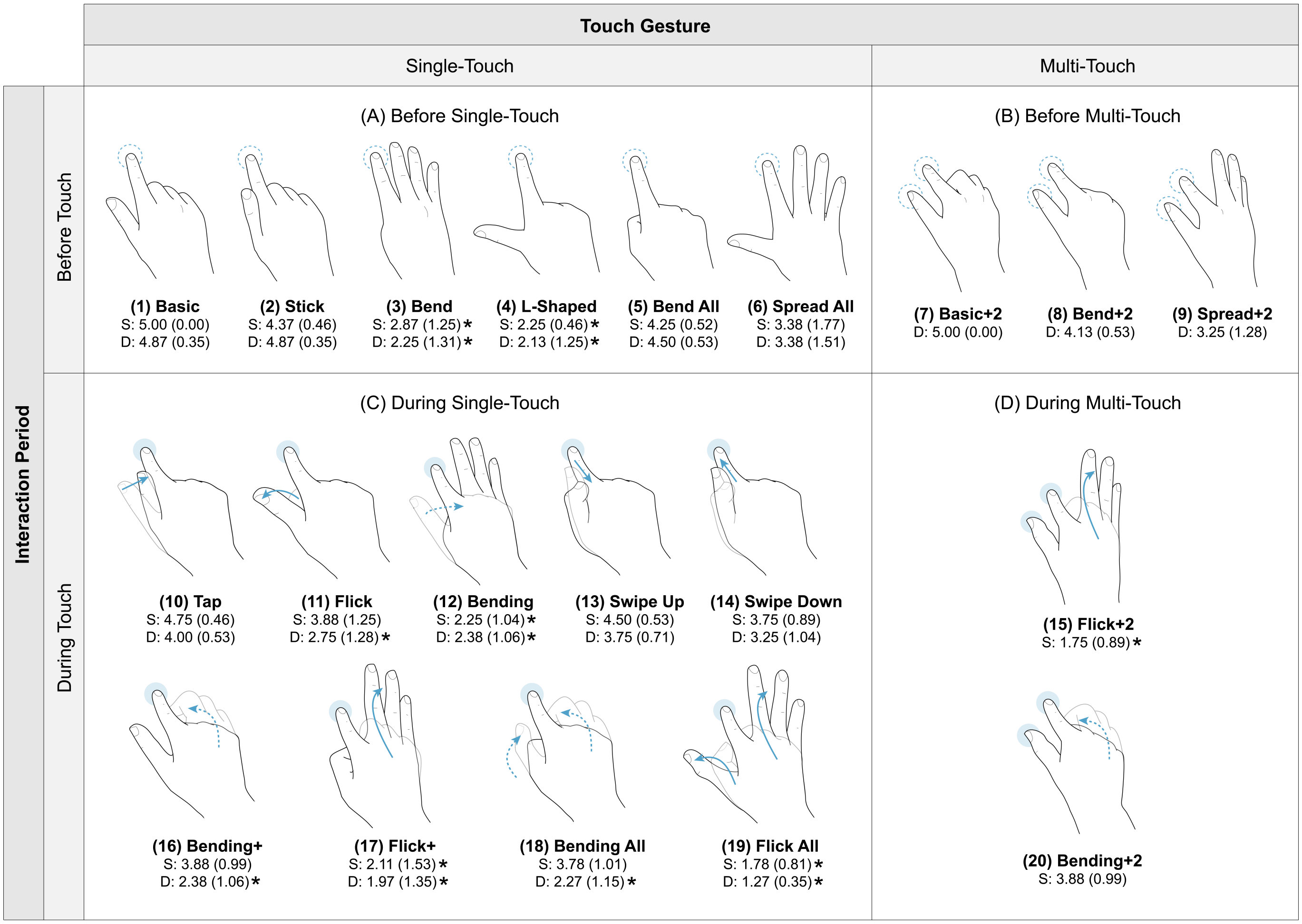


Figure 2. A 2×2 design space was constructed based on conventional touch gestures (single- and multi-touch) and interaction periods (before and during touch). Based on the design space, we present the Touch+Finger gesture set and a summary of user ratings on the ease of performance of each gesture on a 5-point Likert scale (S: static touch gesture, D: dynamic touch gesture, SD in parentheses; 1 = most difficult, 5 = easiest, and *: uncomfortable gestures that received user rating under 3).

EXPLORING TOUCH+FINGER GESTURES

In order to explore Touch+Finger gestures comprehensively, all possible motions of the secondary fingers were examined in each subsection of the design space (Figure 2), without particular consideration of the ease of use. The ease of Touch+Finger gestures will be discussed in the Evaluation section. Below, the 20 Touch+Finger gestures shown in Figure 2 are described in detail.

Each possible case is described in terms of the movement of the primary finger and the secondary finger [8]. The primary finger, in this case the index finger, can either tap the screen or drag on the screen. The terms "static" and "dynamic" are used to differentiate these. On the other hand, secondary fingers, in this case the thumb and the middle+ fingers, can either perform different hand poses before a touch or various in-air gestures during a touch (e.g., tapping, flicking, bending, and swiping). The terms "discrete" and "continuous" are used to describe the manner in which the hand poses or in-air gestures add extra input information (e.g., tapping is discrete input, and swiping up/down is continuous input).

(A) Before Singe-Touch Gestures

Before a single touch with the index finger, users can make a variety of different hand poses with the thumb and the middle+ fingers compared to the basic hand pose ((1) "Basic"), as shown in Figure 2 (A). Since the thumb has a unique ability to rotate [25], it can be moved in various directions, and users can make diverse hand poses with the thumb. For example, the thumb can stick to the index finger ((2) "Stick"), bend inside ((3) "Bend"), or spread outside, making a reverse "L" shape ((4) "L-shaped"). Also, users can make a fist with the thumb and middle+ fingers ((5) "Bend All") or spread them out ((6) "Spread All"). All of these hand poses are used as discrete input information for primary touch interaction. In addition to each of the different hand poses formed with the secondary fingers, users can perform static (e.g., tap) and dynamic (e.g., drag) single-touch gestures with the index finger.

(B) Before Multi-Touch Gestures

Before multi-touch gestures with the thumb and the index finger, users can only make a limited number of hand poses with the middle+ fingers due to their anatomical limitation [25]. As shown in Figure 2 (B), compared to a basic hand pose ((7)

"Basic+2"), the user is able to use the middle+ fingers to make two distinct hand poses such as bending inside ((8) "Bend+2") or spreading out ((9) "Spread+2"). As above, both static (e.g., two-point touch) and dynamic (e.g., pinch and spread) multi-touch gestures can be performed while maintaining each hand pose by using secondary fingers as a discrete input source.

(C) During Single-Touch Gestures

While the index finger is touching the screen, the secondary fingers, i.e., the thumb and the middle+ fingers, can perform a variety of in-air gestures as additional input commands. With the thumb, as shown in Figure 2 (C), users can tap on the index finger ((10) "Tap"), flick with the aid of the index finger ((11) "Flick"), bend inside ((12) "Bending"), and swipe up ((13) "Swipe Up") and down ((14) "Swipe Down") between the distal and proximal sides of the index finger. In terms of using the middle+ fingers, users can bend them ((15) "Bending+") and flick them in the air ((16) "Flick+"). Finally, by using the thumb and the middle+ fingers, users can bend ((17) "Bending All") and flick in the air ((18) "Flick All"). All of these in-air gestures can be utilized as discrete input sources for primary touch interaction. However, some in-air gestures, such as bending and swiping, can also be used as continuous input information. Likewise, users can perform these in-air gestures while performing static and dynamic single-touch gestures with the index finger.

(D) During Multi-Touch Gestures

When the thumb and the index finger are used as primary fingers for multi-touch interaction, the only secondary fingers are the middle+ fingers. This allows for performing the limited in-air gestures such as flick ((19) "Flick+2") and bend ((20) "Bending+2"), as shown in Figure 2 (D). As noted above, these in-air gestures can be employed as discrete input information for primary touch interaction. Nonetheless, the Bending+2 can also be used as continuous input source. In developing the During Multi-Touch gestures, we found that it is difficult for the middle+ fingers to perform in-air gestures while simultaneously performing dynamic touch gestures with the index and thumb fingers. This is because two independent gestures, i.e., primary multi-touch gestures and secondary in-air gestures, require too much attention and effort. Instead, users can apply these secondary in-air gestures to static multi-touch gestures, such as the two-point touch.

Figure 2 shows the Touch+Finger gestures that were explored in the design space. Since not all Touch+Finger gestures are user-friendly, a user study was conducted to investigate the ease of performing Touch+Finger gestures and to discuss ergonomic issues related to them. The results of this study are discussed in the Evaluation section.

A TOUCH+FINGER PROTOTYPE

In order to implement Touch+Finger gestures as new interaction techniques, it is necessary to track the motions of fingers in the air. Therefore, we built a Touch+Finger prototype to detect touch and in-air gestures. While there are a number of sensing techniques to track finger movements in the air (e.g., vision-based techniques [5, 8] and capacitive sensors [12]), our prototype utilized two finger-worn devices with IMU sensors attached [24], which was simple, robust, and reliable enough for an initial exploration of Touch+Finger gestures. This setup was used for the demonstration of several interaction techniques with the gestures, spanning the outlined design space and demonstrating the viability of this approach.

Hardware

Figure 3 shows the prototype, which consists of two ring-like devices with IMU sensors attached, a touch-based device (in this case, a Samsung Galaxy Note 10.1 tablet), and a PC for data processing. The IMU sensor board included 9-axis inertial motion sensors (i.e., an accelerometer, a gyroscope, and a magnetometer), providing the three-axis data from these sensors, as well as yaw, pitch, and roll (maximum 100Hz output rate). The tablet provided the touch input information, such as the number of touch points (e.g., single touch or two-finger touch). The external PC received IMU sensor data through a flexible USB connection for finger tracking, and then sent the finger information to the tablet via a wireless network. The tethered flexbile USB made the ring-like devices less bulky by eliminating the need for a battery and a Wi-Fi module, which minimized any inconvenience to finger movements.

Figure 3. Our Touch+Finger prototype consisted of two ring-like devices with a IMU sensor attached, a touch-based device, and a PC for data processing

Secondary Finger Tracking

To track the motion of secondary fingers in the air, the ring-like device prototypes were worn on the thumb and the index finger. We collected data continuously from each IMU sensor board at a sampling rate of 50Hz for all Touch+Finger gestures (Figure 2). Since secondary gestures, i.e. hand poses and in-air gestures, take about 0.4s to 0.9s to perform, a one-second sliding window was used for performing statistical feature extraction. Inspired by [31], we calculated four statistical features from the sliding window: mean, standard deviation, maximum, and minimum. The same calculation was performed for each sensor value, i.e. three-axis accelerometer, three-axis gyroscope, pitch, and roll. The yaw value was excluded due to its unreliability and a calibration issue [33]. In general, roll and pitch are important for recognizing hand poses. Accelerometer and gyroscope features are useful in capturing amplitude differences of in-air gestures.

Avoiding False Positives
In order to reduce false positive errors in recognizing Touch+Finger gestures, we defined a touch event to initiate when the recognition system was activated. We did not choose to collect pre-sensing data because various hand poses can be instantly detected when a touch occurs. Also, such data could result in erroneous results due to the considerable variation of user gesture performance [27]. Furthermore, starting the system when a touch occurs helps the secondary fingers to avoid collision with unintentional finger movements. This is because the secondary fingers tend to be still unless triggered by the user's intention while the primary finger is touching the screen. Taking all of the above into consideration, we designed the classifier to be activated while a touchscreen detects a touch event.

Gesture Classification
A supervised machine learning approach was used to recognize a total of 20 Touch+Finger gestures. Performance was tested by several basic classifiers such as a decision tree, logistic regression, k-nearest neighbors (k-NN), and a support vector machine (SVM). Overall, the decision tree classifier achieved the best result in the pilot test. This classifier was applied to the prototype for evaluation and demonstration. Figure 4 summarizes the classification module.

EVALUATION
The user study measured the recognition accuracy of 20 Touch+Finger gestures and received the user ratings on the ease of performance for each gesture on a 5-point Likert scale. Semi-structured interviews were also conducted to gather additional feedback.

Participants
Eight participants (five males and three females) ranging in age from 27 to 38 years (M = 32, SD = 4.0) were recruited. All participants had some level of experience with touch gestures, along with the frequent use of mobile devices, such as smartphones and tablets, as well as PC touchpads. However, they had no prior knowledge of the Touch+Finger gestures suggested in this study.

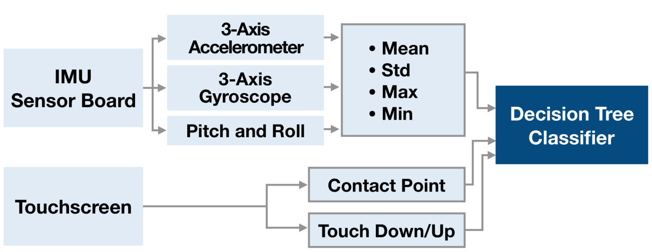


Figure 4. Block diagram of the major components of Touch+Finger gestures' classification module. The calculated IMU sensor values (i.e., mean, standard deviation, max, and min for a one-second sliding window) and touch information (i.e., contact point and touch down/up) are features used for classification.

Procedure
For data collection on Touch+Finger gestures, participants were asked to wear a ring-like device with an IMU sensor attached to both the thumb and the middle finger. The IMU sensor was firmly placed on the center of each finger. Before the beginning of data collection, there was a training session lasting about ten minutes, which was completed as soon as the participants felt familiar with all 20 Touch+Finger gestures. Participants were also asked to check whether or not the tethered USB had any influence on the feasibility and comfort of performing the gestures. Since the ring-like device was not bulky and the wire was flexible enough for the fingers to move freely, none of the participants reported any discomfort in wearing the prototype while performing the gestures. They took part in two data collection sessions, one for the Before Touch gesture set, consisting of 9 hand poses, and the other for the During Touch gesture set, consisting of 11 in-air gestures. In each session, participants were asked to sit in a chair and perform each gesture on a tablet on a flat desk. The order of Touch+Finger gestures was counterbalanced for each session. All of the gestures were recorded with labels for classification.

Session 1: Before Touch Gestures
Data was collected when a primary finger was either static (i.e., tap) or dynamic (i.e., drag or pinch spread) on the screen. For Before Single-Touch gestures, participants were asked to tap the screen with the index finger using six different hand poses shown in Figure 2 (A): (1) "Basic," (2) "Stick," (3) "Bend," (4) "L-shaped," (5) "Spread All," and (6) "Bend All." Ten taps for each hand pose were recorded for all participants. In addition to the taps, participants were also asked to drag for 10 seconds by maintaining each hand pose on the screen (Figure 2 (A)). For Before Multi-Touch gestures, participants were asked to perform pinch and spread 10 times using three different hand poses shown in Figure 2 (B): (7) "Basic+2" (8) "Bend+2" and (9) "Spread+2". After completing each gesture, participants were asked to rate verbally how easy the gesture was to perform on a scale of 1-5 (1 = most difficult, 5 = easiest).

Session 2: During Touch Gestures
As in session 1 above, data was collected when a primary finger was either static or dynamic on the screen. For During Single-Touch gestures, participants were asked to perform each of the nine in-air gestures shown in Figure 2 (C) 10 times while tapping the screen with the index finger: (10) "Tap," (11) "Flick," (12) "Bending," (13) "Swipe Up," (14) "Swipe Down," (15) "Bending+," (16) "Bending All," (17) "Flick+," and (18) "Flick All." They were also asked to perform each of the nine gestures 10 times again while dragging on the screen with the index finger. For During Multi-Touch gestures, they were asked to perform each of the two in-air gestures while performing a two-point touch as shown in Figure 2 (D): (19) "Flick+2" and (20) "Bending+2." Likewise, participants were asked to rate verbally how easy each gesture was to perform on a scale of 1-5 (1 = most difficult, 5 = easiest).

A total of 2,080 gesture samples were collected, including 480 Before Touch gestures (6 single-touch gestures $\times$ 1 static input $\times$ 10 times $\times$ 8 participants) and 1,600 During Touch gestures (9 single-touch gestures $\times$ 2 static and dynamic input $\times$ 10 times $\times$ 8 participants + 2 multi-touch gestures $\times$ 1 static input $\times$ 10 times $\times$ 8 participants). In particular, for dynamic Before Single-Touch gestures, data was collected for 10 seconds for each hand pose while dragging on the screen with the index finger. After completing two sessions, participants were asked to express their overall feedback on Touch+Finger gestures by answering the following questions: "What did you like about Touch+Finger gestures?" "Which gestures were difficult and why?" and "What was it like to perform primary touch and secondary in-air gestures at the same time?" The whole procedure took approximately 40 minutes in total.

Results

Overall, Touch+Finger gestures were classified with a high accuracy of over 99%, and they received both positive and negative comments from the participants.

Recognition Accuracy

For gesture classification, two validations were conducted using all the data from each session: a leave-one-user-out cross-validation and a split-half cross-validation.

We identified whether our recognition approach was user-dependent by conducting the leave-one-user-out cross-validation [11]. One participant's data was set aside as a test set, and the rest were used as a training set to build the model (i.e., a decision tree). For each gesture set, this process was repeated eight times (i.e., all the combinations from the eight participants). The average and standard deviation of the recognition accuracy were then calculated. The results for both gesture sets were 100%, indicating that participants performed the Touch+Finger gestures in an almost identical manner.

For a split-half cross-validation to give a better estimate of the power of our method [27], the gesture samples were randomly divided in half, with one half for training to build a model and the other for validation. This validation was conducted 10 times for both the Before Touch and the During Touch gesture sets to find the average and standard deviation (SD) of the accuracy. This approach achieved nearly perfect classification accuracies of 99.2% (SD = 0.03) and 99.6% (SD = 0.02), respectively. Figure 5 summarizes classification accuracy as a confusion matrix for each gesture set.

Basic	0.99	0	0	0	0.01	0	0	0	0
Stick	0	1	0	0	0	0	0	0	0
Bend	0	0	1	0	0	0	0	0	0
L-Shape	0	0	0	1	0	0	0	0	0
Bend All	0.01	0	0	0	0.99	0	0	0	0
Spread All	0	0	0.02	0	0	0.98	0	0	0
Basic+(2)	0	0	0	0	0	0	1	0	0
Bend+(2)	0	0	0	0	0	0	0.01	0.99	0
Spread+(2)	0	0	0	0	0	0	0	0	1

Tap	0.98	0	0	0	0	0	0	0	0	0	0
Flick	0	1	0	0.01	0	0	0	0	0	0	0
Bending	0.02	0	0.99	0	0	0	0	0	0	0	0
Swipe Up	0	0	0	0.99	0	0	0	0	0	0	0
Swipe	0	0	0	0	1	0	0	0	0	0	0
Bending+	0	0	0	0	0	1	0	0	0	0	0
Flick+	0	0	0	0	0	0	1	0	0	0	0
Bending All	0	0	0	0	0	0	0	1	0	0	0
Flick All	0	0	0	0	0	0	0	0	1	0	0
Flick+(2)	0	0	0	0	0	0	0	0	0	1	0
Bending+(2)	0	0	0	0	0	0	0	0	0	0	1

Figure 5. Confusion matrix using half-test and half-train cross validation: (left) before touch gestures – avg. accuracy 99.4% and (right) during Touch gestures – avg. accuracy 99.6%.

Overall, recognition accuracy was exceptionally high for all the Touch+Finger gestures. This high accuracy of over 99% may be due to the controlled lab environment and the fixed primary finger on the screen. During the data collection process, participants sat in the chair and performed each gesture on a flat desk, which might have prevented alternative angles for the users to perform Before Touch gestures. Also, touching the screen consistently with the primary finger could limit the possible movements of the secondary fingers, potentially leading to almost identical secondary in-air gestures. That is, it should be noted that if we had evaluated our approach with more extensive data in a more natural, real world setting, the classification accuracy would have been lower.

User Feedback

In general, participants gave both positive and negative feedback to Touch+Finger gestures. The result of user ratings is shown in Figure 2.

For Before Touch gestures, participants were able to make all of the hand poses easily except for (3) "L-shaped" and (4) "Bend" while performing both static and dynamic touch gestures with a primary finger. However, most participants had trouble forming (3) "L-shaped" and (4) "Bend" hand poses because these were rather uncomfortable, requiring them to put in more effort to maintain the poses. Specifically, some participants (P1, P4, P5, and P8) reported that the "L-shaped" hand pose required much effort to extend the thumb's joint farther than is naturally possible.

For During Touch gestures, there was a significant difference between static and dynamic touch gestures with a primary finger. While performing the static touch gestures (i.e., tap or two-point touch), participants were able to perform most in-air gestures without any problem, except (11) "Bending," (12) "Flick+," (18) "Flick All," and (19) "Flick+2." Some participants indicated that both bending and flicking gestures were quite stressful because the gestures required much more effort to perform than tapping and swiping. On the other hand, while operating the dynamic touch gestures (i.e., drag on the screen), participants reported that most in-air gestures were difficult. Only a few in-air gestures, such as (10) "Tap" and (13), (14) "Swipe Up/Down," were easy because participants felt that tapping and swiping gestures were simple. In particular, several participants began to feel more comfortable with "Swipe Up/Down" in-air gestures as the gestures became familiar. Nonetheless, most participants had trouble performing the rest of the secondary in-air gestures along with the dynamic touch gestures with the primary finger. Some of them (P1, P6, P7, and P8) expressed concerns that when trying to perform in-air gestures with the thumb, such as flicking and bending, they could not control the primary dynamic touch gesture correctly (i.e., they dragged primary fingers in an unintended direction). This may be because the secondary in-air gestures drew attention away from the primary touch gestures which were being performed at the same time.

INTERACTION TECHNIQUES

In this section, we demonstrate each of the Touch+Finger interaction techniques in the 2×2 design space. For each interaction technique, secondary in-air gestures were arbitrarily utilized as discrete or continuous input sources for both static and dynamic primary touch interactions. Examples of applying the Touch+Finger techniques will be provided, most of which were originally implemented with our own prototype but a few of which refer to examples in prior works.

Before Singe-Touch Technique

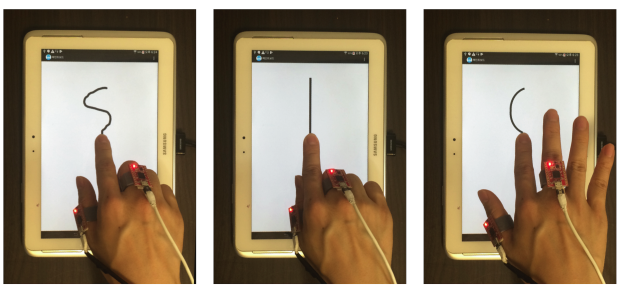
The various hand poses performed by secondary fingers before a touch can enhance a single-touch gesture interaction, allowing for enhanced modality and expressivity. This technique can be applied to static and dynamic single-touch gestures performed with a primary finger.

Enhanced Single Tap

A single tap on the touchscreen with the index finger can have different input commands depending on distinct hand poses. As demonstrated in prior work [5, 11, 13, 23], our technique shows that the tap with a "Spread" hand pose can activate the touch for selecting a file, while the tap with a "Spread All" hand pose would open a context menu for a photo as shown in Figure 1.

Fluid Switching Between Interaction Modes

While keeping a particular hand pose with secondary fingers, users can drag the primary finger on the touchscreen in all directions. In this case, users can easily change their hand poses with secondary fingers, allowing for fluid switching between different input modes. In the drawing application (Figure 6), for example, users could draw a free-form line with a "Basic" hand pose, a straight line with a "Stick" hand pose, or a curved line with a "Spread All" hand pose.



(a) (b) (c)

Figure 6. With the index finger as a primary finger, users can draw (a) a free-form line with a "Basic" hand pose, (b) a straight line with a "Stick" hand pose, or (c) a curved line with a "Spread All" hand pose.

Before Multi-Touch Technique

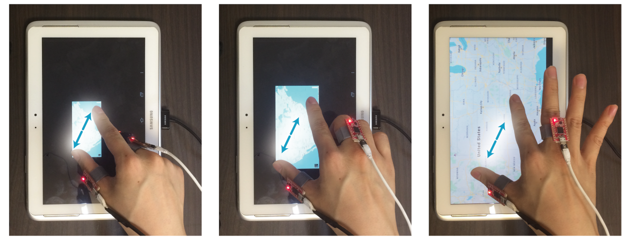
Conventional multi-touch gestures are usually dynamic (e.g., pinch and spread) rather than static (e.g., multi-point touch). Here, by making different hand poses with secondary fingers, additional input information is provided to dynamic multi-touch gestures performed by primary fingers.

Quick Scaling

Multi-touch gestures, such as pinch and spread, are widely used to scale on-screen objects. In this case, different hand poses with the middle+ fingers enable pinch and spread gestures for additional information sources (e.g., different scale values as shown in Figure 7). This technique can be applied to a map viewer application, allowing users to control the zoom level. Instead of pinching several times to zoom in, a single pinch gesture with a "Spread+" hand pose can change the scale from a street view to a world view.

During Single-Touch Technique

While a primary finger is touching the screen, secondary in-air gestures can be used as additional discrete or continuous input sources for the primary touch interaction. Here, we describe both static and dynamic single-touch gestures with features of the additional input sources.

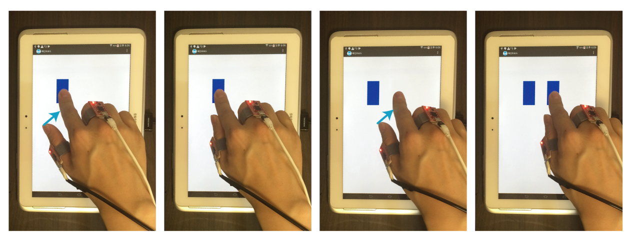


(a) (b) (c)

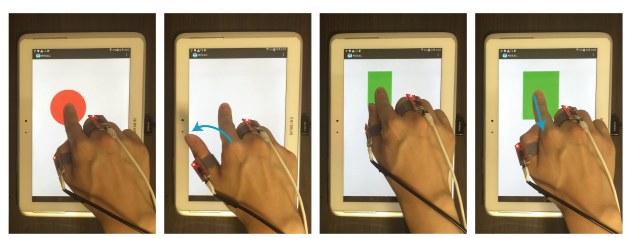
Figure 7. In a single pinch gesture with two primary fingers, users have different scale values by having different hand poses with the secondary finger: (a) small scale with a "Bend+2" hand pose, (b) medium scale with a "Basic+2" hand pose, and (c) large scale with a "Spread+2" hand pose.

Diagram Manipulation

As illustrated in Figure 8, users could control an object on the screen by using in-air gestures while touching a diagram on the screen with the index finger. As an additional discrete input, for instance, the in-air gesture "Tap" activates copy/paste functions for the blue rectangle and the in-air gesture "Flick" deletes the touched diagram (i.e., the red circle). On the other hand, the in-air gesture "Swipe Up/Down" can be used as additional continuous input for the touched diagram (i.e., the green rectangle), allowing for enlarging or shrinking of the object in the diagram. In this case, the size of the green rectangle can be continuously adjusted according to the up-and-down motion of the thumb during the "Swipe Up/Down" gesture.



(a) Tap for copy and paste



(b) Flick for delete (c) Swipe up for enlarge

Figure 8. Users can control the touched object by performing in-air gestures with the secondary finger, in this case the thumb, such as (a) tap for copy and paste, (b) flick for delete, and (c) swipe up for enlarge.

Game: Shooting Bullets on the Go

Secondary in-air gestures can be used as discrete additional input actions while the primary finger, in this case the index finger, is constantly moving on the screen. In the evaluation, P3 suggested that the in-air gesture "Tap" could be applied to an airplane shooting game, in which a user could shoot a bullet with in-air "Tap" gestures while constantly moving the airplane with a primary finger to avoid attack.

An "Expressive" Brush Stroke

Secondary in-air gestures can also provide continuous extra input for dynamic touch gestures with primary fingers. In Expressy [33], users could continuously control the width of a brush stroke by using motions of the user's wrist as a controller while drawing a line. Likewise, as shown in Figure 9, our technique can do the same while drawing a line by using the changes in thumb sensor values when performing in-air gestures "Swipe Up/Down." Unlike Expressy, users could enable a finer adjustment of the width of a brush stroke with this method, as the fingers have more sophisticated motor capabilities than the wrist.

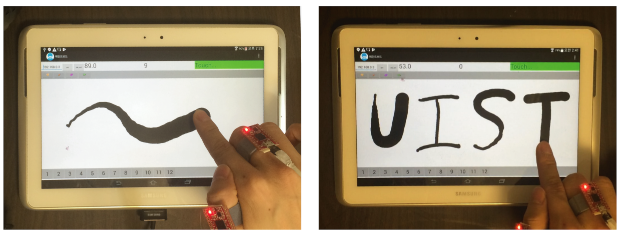


Figure 9. A user can continuously control the width of a brush stroke with secondary in-air gestures "Swipe Up/Down" while drawing a line with the index finger.

During Multi-Touch Technique

As mentioned above, it is difficult for users to operate in-air gestures with secondary fingers concurrently with performing dynamic multi-touch gestures such as pinch and spread. Instead, secondary in-air gestures can be executed when users perform static touch gestures, such as the two-point touch. In this case, the in-air gesture ("Bending+2") can be discrete or continuous input for a two-point touch.

Resizing an Image At Once

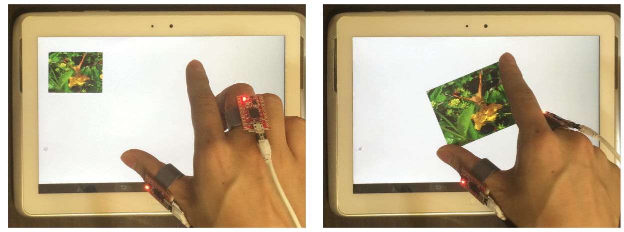
Users can use a secondary in-air gesture ("Bending+2") as a discrete extra input command to augment two-point touch. As shown in Figure 10, users can adjust an image to the exact size they want at the desired location on the screen by using an enhanced multi-touch gesture enabled by in-air gestures. Users determine the size of an image by distancing two fingers, each pointing diagonally across the image. They can insert it at the desired location at once by performing the "Bending+2" gesture with secondary fingers. Compared to conventional methods which require several steps to adjust an image (e.g., enlarge, drag, and rotate), this technique is simpler and more efficient.

Rotating a 3D Object around a Two-Point Axis

The in-air gesture ("Bending+2") can also be a dynamic input action for the two-point touch with the primary fingers. In an example proposed by [10], a user can rotate a 3D figure around an axis by locking the axis with two primary finger points and then rotating the figure around the axis by using continuous bending controls with the middle+ fingers.

DISCUSSION

Touch+Finger gestures extend touch-based user interface capabilities by using the rest of the "idle" fingers. We have shown how these idle fingers can be used as secondary input sources to enhance primary touch interaction. Here, we discuss the issues and implications of our work for the purpose of informing future research.



(a) (b)

Figure 10. A user can adjust an image to exact size at the desired location on the screen at once in the following way: (a) determine the diagonal of the image as the distance between two finger points at the desired location, and then (b) insert it by bending the middle+ fingers ("Bending+2").

Although the current prototype was sufficient for an initial exploration and evaluation of Touch+Finger gestures, there is still room for improvement. Since the ring-like devices were wired to an external PC, a smaller, self-contained form of the ring device is desired. We believe that it is conceivable to further miniaturize the device until it is a standalone wearable ring device like commercial products [14, 20]. Nonetheless, our techniques require wearing multiple rings to track the motions of secondary fingers, which may be somewhat impractical for some users. This could be addressed in the future by exploring alternatives such as a depth camera [5, 18] or capacitive sensors [17] to detect multiple finger movements. For example, the hover-sensing techniques used in [17] can track fingers up to 35mm above the screen, which might be applicable to some of the Touch+Finger gestures.

In terms of evaluation, we found that there is a trade-off between the discomfort of performing secondary in-air gestures and the high classification accuracy. In general, users have their own preferences for performing any finger gesture in the air, and the way the gestures are performed may vary considerably, which might lower the recognition accuracy. However, interestingly, although touching the screen consistently with the primary finger tends to cause discomfort in performing secondary in-air gestures, it helped us to achieve high recognition accuracy. We conjecture that the fixed primary finger on a touchscreen while performing secondary in-air gestures may have restricted the possible secondary finger movements, allowing users to perform the gestures in an almost identical manner. Also, since secondary fingers tend to be still unless triggered intentionally by the user while touching the screen with primary finger, this might also have helped to avoid collisions caused by unintentional finger movements.

Our work has focused on exploring Touch+Finger gestures using the thumb and/or the index finger as primary fingers. We believe that more extensive Touch+Finger gestures can be developed by using a finger other than the index finger as the primary finger. For example, if a user touches a screen with the middle finger as the primary finger, the secondary fingers are the thumb, the index, the ring, and the little finger. The thumb and the index finger are more independently movable since they have their own muscles for stretching [4, 25]. Hence, the thumb and index finger can together perform a variety hand poses or in-air gestures, which we will explore in future work.

The Touch+Finger gestures proposed in this paper were intended for use on a tablet device. In the future, it would be interesting to investigate potential combinations of the gestures on other devices. For instance, we believe that Touch+Finger gestures can particularly be useful for small screen devices, such as smartwatches and mobile phones, because these gestures can effectively expand their limited input space. In addition, Touch+Finger gestures can be applied to improve interaction with virtual reality (VR) headsets and head-mounted devices such as Google Glass, where secondary fingers could be used to expand the input space, providing advanced modalities and added expressivity. Also, these techniques can be applied on a laptop interface. For example, users can perform copy-and-paste actions with a secondary in-air gesture ("Tap") on a laptop touchpad instead of using the conventional Control + C and V keys or the right-click.

In addition, we plan to explore possibilities of combining Before Touch and During Touch gestures. Our current system cannot support the simultaneous use of both gestures. That is, when drawing a straight line with the "Stick" hand pose, users cannot control the width of the line with using in-air gestures as they have to maintain the pose to draw the line. We believe that assigning different roles to each secondary finger might provide a solution. When drawing the line with the index finger, users can use the thumb to perform in-air gestures to control the width of the line and employ the middle+ fingers to make different hand poses for a particular line type. Users may draw a straight line while controlling the width of a brush stroke with "Swipe Up/Down" gestures, as shown in Figure 9. Combinations like these will require further research on the switch between Before Touch and During Touch gestures.

These Touch+Finger techniques can further enhance the efficiency and performance of the input operation in handling many objects on the screen. For example, if a user intends to enlarge one of many objects on a screen, he or she can touch the object with primary fingers and perform in-air gestures to enlarge it. Conventional techniques require visual user interfaces and require the user to take additional steps to perform such a task, e.g., selecting and dragging the object with the aid of visual cues, opening a context menu, making different menu selections, etc.

Last but not least, our work can still benefit from further research. Although we collected user feedback on Touch+Finger gestures, a formal user study of these interaction techniques is required. In particular, some of our proposed interaction techniques (e.g., quick scaling and resizing an image at once) can be evaluated in comparison with existing techniques. Also, in the evaluation, some participants reported that they had some trouble controlling a drag on the touchscreen when they tried to operate simple in-air gestures such as taps. In future work, we will examine how to control dynamic touch gestures while performing in-air gestures. Finally, we would like to evaluate the recognition system with more data in a real-world setting.

CONCLUSION

Since not all fingers on one hand are engaged in touch interaction, the rest of the "idle" fingers can be used to enhance touch gestures. In this paper, we explored the possibility of using these idle fingers to provide additional information to both before and during primary touch interactions. Users can make a variety of hand poses before a touch and perform in-air gestures during touch interaction, which adds modality and expressivity to the primary touch. We developed a total of 20 Touch+Finger gestures based on the ergonomics and biomechanics of the human hand, and evaluated them on recognition accuracy and user ratings. Lastly, we demonstrated several examples that extend touch-based user interface capabilities with the idle fingers, supporting more expressive interaction.

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