# MagPie: Extending a Smartphone's Interaction Space via a Customizable Magnetic Back-of-Device Input Accessory

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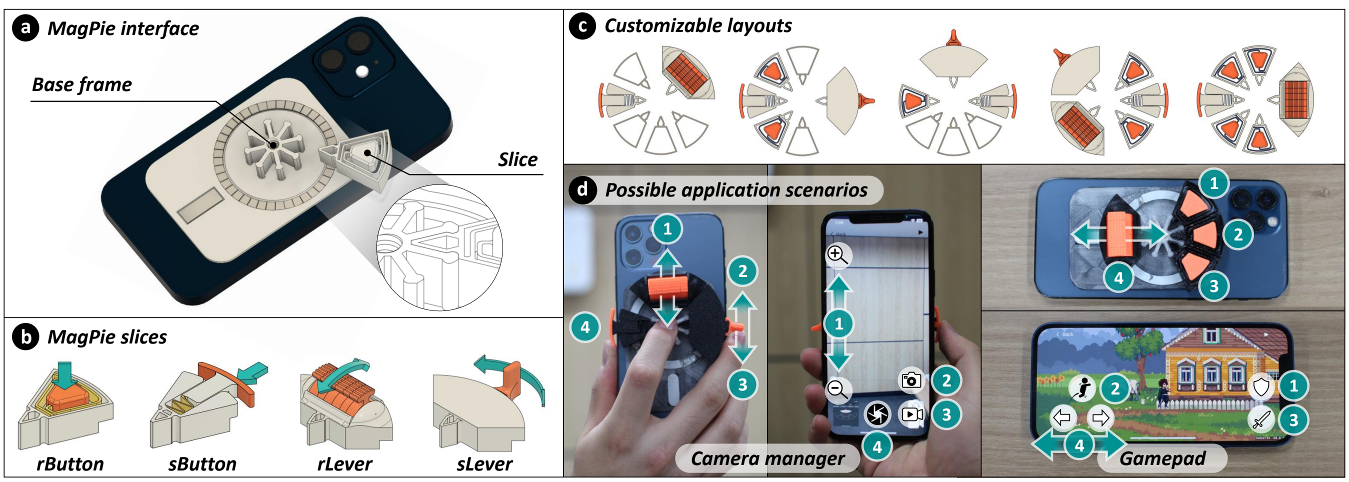


**Figure 1: MagPie and its applications. (a) MagPie is a smartphone accessory for Back-of-Device interaction, which can be attached to any MagSafe-enabled smartphones. (b) MagPie offers a rich set of modular tangible interfaces, which support natural and intuitive interactions with tactile feedback. (c) Users can customize their interaction space by combining a family of MagPie slices as desired. (d) The layout of MagPie can be reconfigured according to the application scenario. In each scenario, MagPie slices are mapped with the application's specific functionalities. See more diverse application scenarios in Section 5.1.**

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## Abstract

Back-of-Device (BoD) interfaces have emerged as a promising solution to free up screen real estate in smartphones by offloading


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interactions from the display to the back, thereby reducing reliance on on-screen interfaces. However, existing BoD solutions face limitations, such as requiring specialized hardware, consuming excessive power, or offering limited input vocabularies. We introduce MagPie, a novel BoD interface that leverages the magnetic phenomenon induced by MagSafe, part of the wireless charging standard. Users can seamlessly attach MagPie to MagSafe-enabled smartphones and interact using tangible, modular interfaces that generate unique magnetic signals upon activation. MagPie then detects these signals and recognizes the input through magnetic sensing. Our experiments with real-world users demonstrate that *i*) MagPie achieves high performance in accuracy, usability, deployability, responsiveness, and robustness across diverse environments, and *ii*) its tangible, intuitive, and customizable design opens up possibilities for a whole new class of smartphone interaction scenarios.

## CCS Concepts

• **Human-centered computing → Interaction devices**; • **Hardware → Haptic devices**.

## Keywords

Back-of-Device Interaction. Tangible User Interface, Magnetic sensing

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## 1 Introduction

One major trend in smartphone design is to maximize screen real estate. For example, bezels have been minimized to increase display area and thus create a more immersive viewing experience. Following this trend, researchers have proposed Back-of-Device (BoD) interfaces that extend smartphone input space to the back. These interfaces free up the display for primary content by reducing the need for on-screen user interface elements, such as virtual buttons. However, the existing BoD solutions often rely on dedicated hardware requiring a power supply [6, 16, 23, 24, 34, 39, 45], consume significant energy [9, 36, 38, 41, 46], support limited input vocabularies [15, 48, 49], or obscure part of the display [43].

To overcome these limitations, we introduce MagPie, a novel BoD interface to leverage MagSafe technology, which embeds a circular magnet array on the back of a smartphone. This unique magnetic structure allows seamless attachment of magnetic accessories to the device's back, boosting the emergence of various kinds of accessories and also unlocking new possibilities for BoD interaction (e.g., functional connections between MagSafe accessories and smartphones [12]). Building on this potential of MagSafe, MagPie further enriches the BoD interaction experience by turning a smartphone's back into a tangible input interface (see Figure 1). The design of MagPie is inspired by our preliminary observation that attaching ferromagnetic objects to a MagSafe magnet ring causes noticeable changes in the surrounding magnetic field, which further vary with the displacement of the attached objects. MagPie consists of *i*) a *base frame* and *ii*) *MagPie slices*. The frame, equipped with a magnet ring, snaps onto a MagSafe-enabled smartphone and serves as the base to fix the slices. The slices are BoD input modules, such as buttons, that use ferromagnetic plates to convert a user's mechanical inputs into magnetic signals. For example, when a MagPie button is pressed, the plate at the bottom of the button touches the magnet in the frame, causing changes in the magnetic field. These variations are captured using the smartphone's built-in magnetometer and analyzed to identify the BoD input.

This interface design based on MagSafe technology and magnetic sensing inherently comes with benefits in terms of deployability and energy efficiency. It is compatible with any MagSafe-enabled smartphones, including smartphones equipped with a MagSafe-like case[1]. Also, using a smartphone's built-in magnetometer requires no additional power supply and consumes only a few mW [21], much lowering battery concerns compared to other vision or acoustic-based approaches.

Despite these benefits, there are several considerations to be addressed in designing MagPie. First, as illustrated in Figure 1, the design of MagPie input components, i.e., a base frame and MagPie slices, prioritize safety, accuracy, and usability as follows:

- *Safety - interference-minimized design.* To prevent interference with or damage to a smartphone's components, MagPie follows the design guidelines for MagSafe accessories [3]. For instance, we use only small ferromagnetic plates to avoid generating additional magnetic fields and limit the amount of the magnetic field variations induced by MagPie. Furthermore, MagPie alters the magnetic field only during BoD interaction. That is, it keeps the magnetic field unchanged before and after the interaction, preventing unintentional recalibration of the smartphone's internal sensors, such as magnetometers.
- *Accuracy - tangible design.* BoD interfaces are prone to frequent input errors, as their interaction space is usually hidden from a user's view during operation. We address this problem through the tangible design of MagPie slices, e.g., physical buttons, which provides tactile feedback. This feedback helps users not only confirm their actions but also put their fingers to correct interaction points, thus reducing the occurrence of input errors.
- *Usability - modular, intuitive, and customizable design.* MagPie offers users a rich set of modular MagPie slices. These slices include buttons and levers that support natural and intuitive interactions such as clicks and scrolls. In particular, we diversify input mechanisms for each slice type, further enriching input vocabulary. MagPie also enables users to easily connect or disconnect slices from smartphones. In other words, users can customize their BoD interaction space as desired and even depending on the application scenario.

Second, we implement a magnetic signal processing method to detect and identify MagPie inputs, which provides a high level of

[1]According to the Wireless Power Consortium (WPC) [40], the next generation universal wireless charging technology, Qi2, will incorporate MagSafe. This will lead to the emergence of MagSafe-enabled smartphones manufactured by diverse smartphone vendors.

*i*) robustness through sensor-fused noise cancellation, *ii*) responsiveness via a simple intensity-based detection and identification algorithm, and *iii*) usability with minimal user-involved calibration.
**Contributions.** In summary, our contributions can be listed as follows:

- To the best of our knowledge, this is the first exploration of transforming a smartphone's back into tangible and customizable user interface based on MagSafe technology.
- We propose MagPie, a BoD interface for smartphones with a novel hardware design that addresses the considerations on safety, accuracy, and usability.
- We conducted comprehensive experiments with a prototype implementation of MagPie running on both Apple and Android smartphones. The results show that MagPie achieves high accuracy of identifying inputs (97.1% on average) with minimal user-involved calibration and maintains accuracy across diverse situations and environments.
- We performed in-depth user studies with 14 participants to assess the overall usability of MagPie, demonstrating that it can open up possibilities for a variety of intriguing BoD interaction scenarios in the real world.

## 2 Related Works

In this section, we introduce previous works that extend the interaction dimensions of a smartphone beyond its touchscreen and clarify how our work differs from them.

### 2.1 MagSafe-based interfaces

MagID [12] introduces a new class of interaction mechanisms using MagSafe technology. Specifically, it identifies attached MagSafe accessories by analyzing magnetic field variations during their attachment and supports a connection between the accessories and software functionalities, e.g., performing pre-defined tasks based on the attached accessory. Its magnetic noise cancellation technique that uses a smartphone's magnetometer and gyroscope together ensures accurate accessory identification even in noisy environments. While MagPie similarly leverages MagSafe technology and magnetic sensing as a means for enabling interaction with smartphones, it further extends the functionality of smartphones by turning their back into a tangible and customizable user input interface, especially with its novel hardware design.

### 2.2 Back-of-Device interfaces

Expanding interaction to the back of smartphones has been explored to alleviate screen occlusion caused by fingers or other objects. One approach involves attaching additional hardware, such as keypads [23, 24, 34, 45], touchpads [35, 50], or other sensors [6, 16, 39]. However, they require dedicated electronic devices or power supplies, limiting their practicality and compatibility with off-the-shelf smartphones. Other methods leverage a smartphone's built-in sensors for BoD interaction. Rear cameras [9, 41, 44] and IMU (Inertial Measurement Unit) sensors [15, 48, 49] are used to recognize BoD finger gestures, while VSkin [36] and StruGesture [38] detect taps and swipes via sound captured by embedded microphones. However, these approaches are constrained by limited input vocabularies (such as basic tap and swipes) and high battery consumption due to continuous use of energy-intensive sensors. Some works aim to enrich input vocabulary using supplementary devices. For example, BackTrack [43] converts the back of smartphones into touch interfaces by connecting specific screen areas with electrodes installed on the back. CamTrackPoint [46] uses a 3D-printed ring on the camera bezel to track finger gestures based on the light through a finger. While innovative, these methods face challenges, such as reduced usability from touchscreen occlusion for BoD interaction [43] or high energy demands from continuous camera usage [46]. We overcome these limitations by presenting a customizable BoD interface providing a richer input vocabulary and improved usability without extra sensors or separate power supplies.

### 2.3 Around-Device interfaces

Numerous studies have explored to extend interaction dimensions to the space around smartphones. Some approaches involve adding dedicated sensors, such as infrared [7, 25] or radar [11, 18], to detect hand gestures. However, these sensors are not available on commercial smartphones, limiting deployability. Alternative studies propose compact, portable interfaces that utilize a smartphone's built-in sensors. For example, ring-shaped accessories [10, 27, 32] enable smartphones to track fingers in their surrounding space but require users to wear the rings continuously. Vidgets [42] provides various input mechanisms through small widgets, though it still requires a dedicated case for widget attachment. In contrast, MagPie enhances deployability via *i*) its easy-to-attach and detach design based on MagSafe and *ii*) the use of sensors available on most commercial smartphones.

### 2.4 Magnetic interfaces

Traditional magnetic interfaces, such as Hall-effect switches and joysticks [13, 28, 29], require close proximity (a few millimeters) between sensors and interaction modules to ensure robustness against noise. MagPie, however, uses a smartphone's built-in magnetometer to detect BoD inputs from several centimeters away, making it more susceptible to magnetic noise from movements and the environments. MagPie addresses this issue with the use of a magnetic noise canceling algorithm [12] that fuses magnetometer and gyroscope data.

Magnetic sensing has also been explored to enable innovative interactions, such as in-air gestures [1, 22, 26], 3D inputs [8, 37], and other novel forms of user interface [2, 5, 19, 33]. For example, MagneTips [26] tracks a magnet on a fingernail for in-air gestures, while MagGetz [19] analyzes magnetic fields from magnet-equipped control widgets for tangible interactions. TetraForce [37] detects force inputs on a smartphone by estimating magnet displacement in a specialized case. However, they rely on strong magnets, such as neodymium, which can potentially lead to device malfunction. In contrast, MagPie employs small ferromagnetic plates, which do not generate additional magnetic field, and adheres to the standard MagSafe guidelines, to avoid interference or damage to a smartphone's internal components.

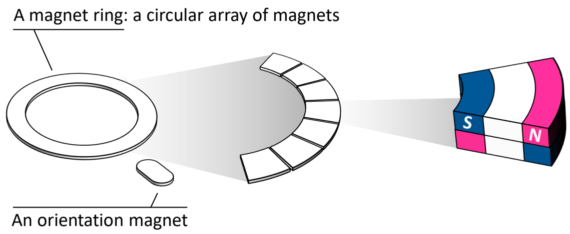
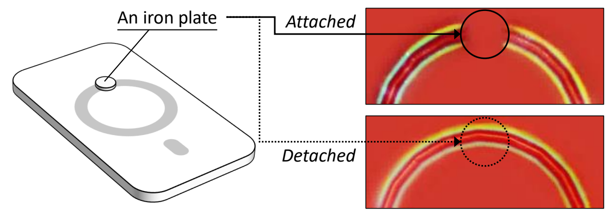
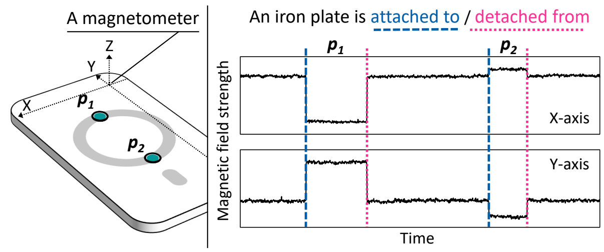



**Figure 2: Typical structure and polarity characteristics of MagSafe.**




(a) Magnetic shielding effect of a ferromagnetic metal on a magnet ring. The magnetic field was measured using a magnetic observation film.




(b) Magnetic field variations when attaching/detaching an iron plate to/from a magnet ring. We measured the magnetometer field strength using a smartphone's built-in magnetometer.

**Figure 3: Investigation of magnetic shielding effects. In all experiments, we used an iPhone 12 smartphone and a circular iron plate with a thickness of 0.8 mm and a diameter of 6.4 mm.**

## 3 Preliminaries

MagSafe has become the technology of choice for all smartphones. Any smartphone with a MagSafe-like case turns into a MagSafe-enabled smartphone. Additionally, with its integration into Qi2, the next-generation universal wireless charging standard [40], MagSafe will be compatible with various devices, including Android smartphones. In light of this trend, this section first describes MagSafe technology and explores the feasibility of leveraging this universal technology as a key enabler of BoD interaction.

### 3.1 MagSafe Technology

MagSafe, introduced by Apple, involves magnets on the back of smartphones to enable secure accessory attachment and faster wireless charging. Specifically, it includes two types of magnets, *a magnet ring* and *an orientation magnet*. The magnet ring is a circular array of magnets with alternating poles (see Figure 2). It creates magnetic fields that allow MagSafe accessories, equipped with a magnet ring, to snap onto smartphones seamlessly in any orientation. On the other hand, the orientation magnet serves as an anchor point for aligning accessories, which require attachment at a specific angular position, such as rectangular wallets.

**Design guidelines for MagSafe accessories.** Apple provides official design guidelines for MagSafe accessories [3]. Here, we highlight some notable points among these guidelines:

- Accessories should minimize the use of additional magnets and metal components to prevent magnetic interference with a smartphone's internal sensors such as magnetometer and camera. Such interference can disrupt sensor operation, trigger frequent recalibration, and reduce both usability and energy efficiency.
- Accessories exceeding 30 mm from the center of the ring to the top edge of a smartphone must maintain a clearance of at least 5 mm from the back of the device. Otherwise, they may come in contact with the smartphone's rear camera, causing scratches and potential damage.

### 3.2 Feasibility of enabling BoD interaction on MagSafe-enabled smartphones

A magnet ring on a smartphone's back allows ferromagnetic objects, such as iron plates, to be attached to the device. When these ferromagnetic objects are attached, they redirect the magnetic field exerted by the ring due to their high permeability [47]. As shown in Figure 3(a), even a small, thin metal plate can reroute the magnetic flux lines from a magnet ring and act as a magnetic shield, preventing the line of flux from passing through the plate.

Such magnetic changes are then sensed by the smartphone's built-in magnetometer due to its proximity to the magnet ring. Let $m_i$ denote a discrete-time magnetic signal measured by the magnetometer at the $i$-th time instant ($t_i$). It is modeled as:

$$m_i = a^S \cdot m_i^N + b^H + \eta_i, \quad (1)$$

where $m_i^N$ is the Earth's magnetic field vector in the local frame of the magnetometer, $a^S$ is a matrix for soft-iron interference, $b^H$ is a hard-iron bias caused by an external magnetic field, and $\eta_i$ is random noise. As shown in Figure 3(b), $m_i$ abruptly changes when an iron plate is attached and detached. This is because the attachment and detachment alter the magnetic field produced by the magnet ring, i.e., the external magnetic field, leading to fluctuations in $b^H$. Additionally, $m_i$ varies differently depending on where the plate is mounted due to localized magnetic shielding. For example, the magnetic signal varies more significantly when attaching the plate closer to the magnetometer (e.g., $p_1$) because the magnetic field emitted by the magnets near the sensor is shielded.

These observations open up the possibility of identifying a ferromagnetic plate's attachment location through magnetic sensing. Figure 4 shows that even subtle displacement of the plate near the magnetometer (e.g., from location 1 to location 2) causes noticeable variations in $\Delta m_x$ and $\Delta m_y$. In contrast, as the distance from the sensor increases, the difference decreases, making it harder to pinpoint the attachment location of the plate. However, one important

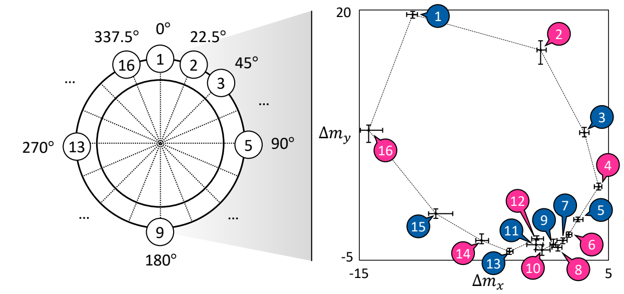



**Figure 4: Magnetic field variations depending on the attachment location of an iron plate. $\Delta m_x$ and $\Delta m_y$ are the amount of sudden changes in X- and Y-axis magnetic signals, respectively. Note that for each location, we collected a set of $\Delta m_x$ and $\Delta m_y$ by attaching the plate 10 times. We then used their mean, minimum, and maximum values as the points and the ends of the whiskers in the plot.**

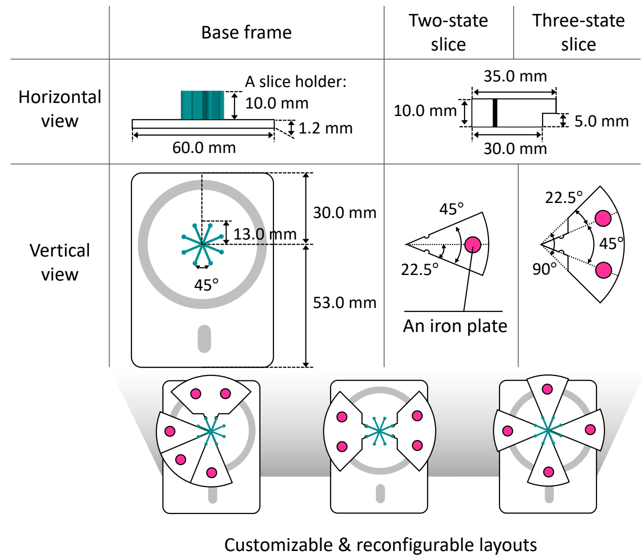



**Figure 5: Structure of MagPie components: a base frame and MagPie slices.**

observation is that the magnetic signal still shows distinguishable changes between distant positions (e.g., an angular difference of 45° in the magnet ring coordinate). Note that similar phenomena are also observed in other smartphones, e.g., iPhone 14 Pro, despite different form factors.

# 4 MagPie Design

We design MagPie as a MagSafe input accessory that has mechanical structures, such as buttons, with MagSafe magnets and ferromagnetic plates. It firmly attaches to a MagSafe-enabled smartphone and converts a user's mechanical BoD input (e.g., pressing a button) into a corresponding magnetic signal using the magnet ring and plates together. The signal is then captured by the smartphone's built-in magnetometer and used to build a classification model (in a calibration phase) or to identify the BoD input (in an interaction phase). That is, MagPie has advantages in terms of deployability thanks to its MagSafe-compatible design and the use of magnetometers available in most smartphones.

In the remainder of this section, we explain how MagPie also meets other design requirements, including safety, usability, accuracy, and responsiveness, through its hardware and software design.

## 4.1 Input Accessory Design

Our input accessory consists of two key components: *a base frame* and *MagPie slices* (see Figure 5). The frame is a base to hold input modules and snaps seamlessly onto the back of a smartphone using two built-in MagSafe magnets (a magnet ring and an orientation magnet). The MagPie slices are mechanical interfaces that can be easily coupled or decoupled from the frame. They are modeled into two types based on the number of input states:

- *Two-state slices.* These slices support two input states using a single iron plate. In the idle state, the plate is either detached from or attached to a frame's magnet ring. When activated, the contact state between the plate and ring changes (e.g., from detachment to attachment or vice versa). That is, each state has different magnetic properties.
- *Three-state slices.* Another input module supports one idle and two different active states using two plates in different positions. In each active state, a different plate contacts the ring, resulting in the generation of unique magnetic signals for each state.

The design of MagPie prioritizes safety, usability, and accuracy as follows.

**Safety-aware design.** First, MagPie components comply with the dimensional guidelines of MagSafe accessories [3] to prevent potential damage to smartphones. A frame does not exceed 30 mm from the center of its magnet ring to avoid interfering with the smartphone's rear camera. However, MagPie slices slightly exceed the dimensional limit to expand the interaction area while maintaining a 5 mm clearance to prevent scratches. Second, we minimize magnetic interference caused by MagPie components. During interaction, slices just redirect the magnetic field exerted from a frame's magnet ring using their plates, i.e., without generating extra magnetic fields. To further reduce magnetic interference, we keep the size of the plates small (e.g., a radius of 3.2 mm and a thickness of 0.8 mm), but only so much that the accuracy of input recognition is not compromised. Additionally, slices are designed to return their idle state after each interaction by using elastic materials such as springs. This implies that the magnetic conditions around a smartphone remain the same before and after the interaction, eliminating the need for recalibrating the smartphone's sensors.

**Accuracy-aware design.** MagPie slices are designed as tangible interfaces that provide tactile feedback, such as pressing a button. This feedback allows users to confirm their actions without relying on visual or auditory cues, reducing errors in BoD interfaces, which are not visible during use. In addition, MagPie slices have an angle of 45 degrees (if they are two-state slices) or 90 degrees (otherwise), which allow up to eight slices to be combined on MagPie. A further decrease in the angle might enable building a richer set of slices,

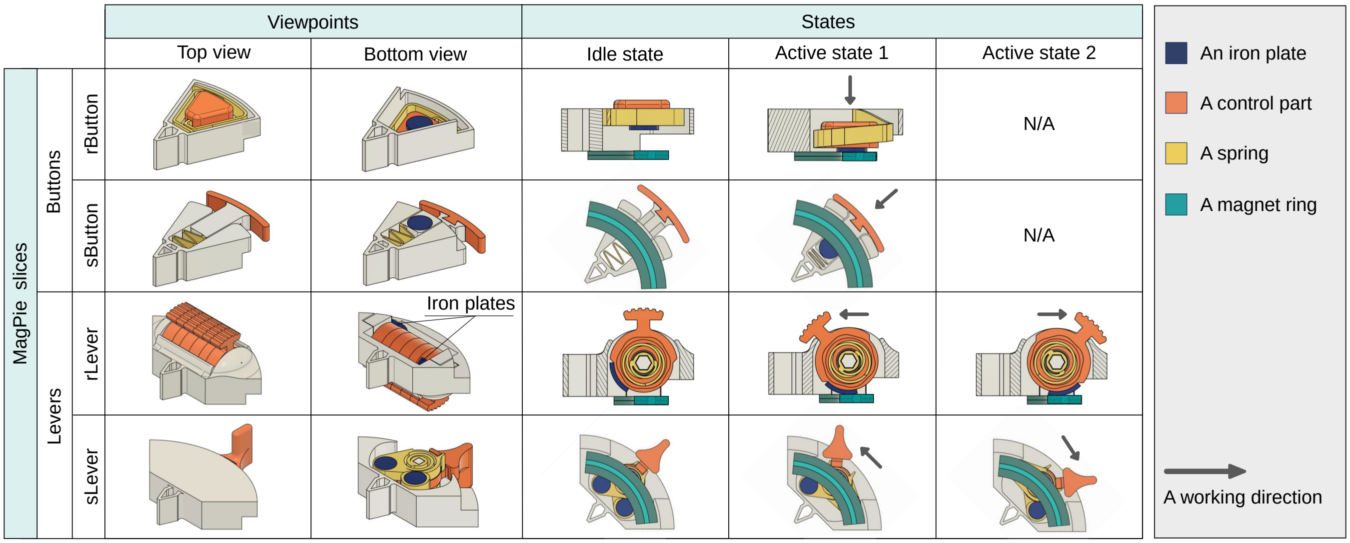



**Figure 6: Tangible MagPie slices which incorporate iron plates, control parts (e.g., handles), and springs.**

but would cause difficulties in distinguishing inputs on different slices because their plates are placed too close together to make noticeable changes in magnetic signals as discussed in Section 3.2. Therefore, we maintain an angle difference of more than 45 degrees between any two plates by configuring the angle and plate location of MagPie slices as shown in Figure 5.

**Usability-aware design.** MagPie slices are modular, allowing users to customize their BoD interaction space by freely combining a family of slices, and even reconfigure it anytime and anywhere. We further enhance the usability of MagPie by introducing various types of interface designs (see Figure 6), which can enrich input vocabulary, as follows:

- *Button slices.* Button slices have a structure of typical push buttons. They are categorized into two types, a rear button (rButton) and a side button (sButton), based on their input mechanism.
  - *rButton.* An rButton supports vertical inputs. When it is pressed, its flat spiral spring is extended downwards, causing the plate attached to its bottom to touch a frame's magnet ring and produce magnetic field changes. When released, the spring returns to its initial position, restoring the magnetic field.
  - *sButton.* An sButton is pressed (in an active state) and released (in an idle state) horizontally using a zigzag spring. In particular, an iron plate at its bottom keeps contact with a magnet ring in the idle state and detaches from the ring when the button is pressed.
- *Lever slices.* Lever slices are three-state slices that support diverse input states through rotational movements. They are designed into two types, a rear lever (rLever) and a side lever (sLever), with different rotational structures.
  - *rLever.* An rLever supports two types of user input (pushing forward and pulling back) using a spiral torsion spring. When a user rotates the lever, the spring is twisted along the input direction. In particular, depending on the direction, the plate positioned at a different location contacts with the magnet of the frame, generating unique magnetic signals.
  - *sLever.* An sLever rotates in clockwise or counterclockwise directions. These rotational inputs are enabled by two spiral torsion springs installed inside the lever and two plates attached to the tip of each spring. When the lever rotates, one of the springs is twisted, making its plate move toward the magnet ring on the frame and finally causing magnetic variations.

Note that our interface design draws inspiration from daily smartphone interactions, such as tapping and swiping. Tapping is mirrored as button presses and swiping, a directional movement, is adapted to the movement of levers. This ensures natural and intuitive user experience by maintaining consistency with traditional smartphone interactions. Moreover, we expect that the vocabulary of MagPie can be further enhanced by introducing a broader range of slices. One example is a dial slice that can offer a playful user experience like setting a cooking timer or unlocking a screen.

## 4.2 Magnetic-based BoD Input Sensing

Once a MagPie slice is triggered, we first detect the input event, called MagPie input, by analyzing sensor streams collected from the smartphone's built-in magnetometer. We then take a magnetic signature for the event and create a set of training data (in a calibration phase) or identify the slice that produces the signature (in an interaction phase).

**Noise robust MagPie input detection.** A magnetic signal $m_i$ is influenced by not only MagPie inputs but also various factors, including a user's rotational movements and environmental changes as illustrated in Figure 7. Therefore, as a preliminary step for detecting inputs, we discard such noise from $m_i$ by using magnetometers and gyroscopes together[2]. Assume that the initial parameters for magnetic interference from surrounding environments, denoted as

[2]This sensor-fused noise cancellation approach is conceptually similar to the technique proposed in [12].

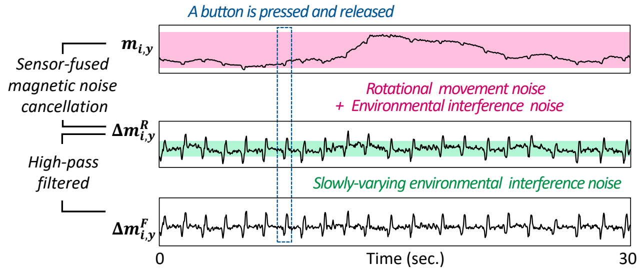



**Figure 7: Orientation-independent and noise-robust signature extraction. The Y-axis magnetic signal was obtained by repeatedly pressing and releasing a button slice coupled to the bottom side of a frame while walking around a corridor.**

$a^S_0$ and $b^H_0$, are obtained in a calibration phase. We first utilize the parameters to correct for the environmental magnetic interference as follows:

$$m^C_i = (a^S_0)^{-1}(m_i - b^H_0), \tag{2}$$

where $m^C_i$ is the calibrated magnetic signal. We then measure $\Delta m^R_i$, the amount of changes between $m^C_i$ and $m^C_j$, while minimizing the effect of the rotational movement noise based on the following SFNC algorithm:

$$\Delta m^R_i = m^C_i - \Delta q^{-1}_{j,i} \cdot m^C_j \cdot \Delta q_{j,i}, \tag{3}$$

where $\Delta q_{j,i}$ is the quaternion to represent a rotation change of the smartphone between $t_j$ and $t_i$ measured using the gyroscope readings collected from $t_{j+1}$ to $t_i$ [20] and $j$ is $i - l^D$. Note that we set $l^D$ to a sample length of 100 ms based on our preliminary observation that $m_i$ varies suddenly (within less than 100 ms), when a ferromagnetic plate is attached to or detached from the smartphone's magnet ring.

$\Delta m^R_i$ might be still erroneous as shown in Figure 7. Such errors mainly occur when a user moves around indoor environments where have local asymmetry of ferromagnetic and electromagnetic elements. However, we observed that the environmental interference noise caused by the user displacement varies slowly even in complex indoor scenarios, e.g., going up and down stairs, while MagPie inputs make abrupt magnetic changes. Based on this empirical observation, we obtain $\Delta m^F_i$ by filtering out the slowly-varying noise from $\Delta m^R_i$ with a Butterworth high-pass filter, which has an order of 1 and a cut-off frequency of 0.5 Hz.

Given $\Delta m^R_i$, MagPie detects an input at $t_i$ by verifying three conditions: *i*) none of the MagPie slices in a currently-used layout is in an active state[3], *ii*) the magnitude of $m^F_i$, i.e., $||\Delta m^F_i||$, is greater than a detection threshold ($\theta^T$) configured in a calibration phase. Here, we use the magnitude, instead of each axis value, to detect inputs made on any locations that cause significant magnetic field variations, but in different directions as illustrated in Figure 4, and *iii*) the magnitude is a local maximum value among the magnitudes in a range from $t_i - 50ms$ to $t_i + 50ms$.

**Lightweight MagPie input recognition.** Once a MagPie input is detected at $t_i$, MagPie uses $\Delta m^F_i$, an orientation-independent

[3]MagPie supports a single input mode where at most one slice can be activated at a time.

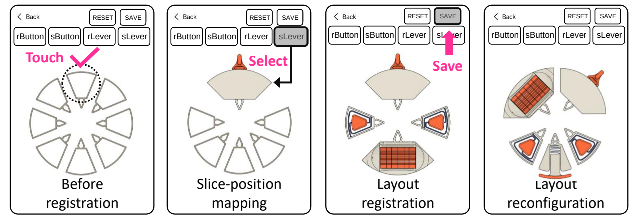



**Figure 8: Graphical user interface for registering a MagPie layout.**

and noise robust three-axis magnetic feature, as the signature for recognizing the input. Suppose that during a calibration phase, a set of training data $\Delta m^T_j$ is collected for each slice in the current layout. MagPie performs input recognition using a one-nearest-neighbor method by finding the training sample with the shortest normalized distance ($d^*$) to $\Delta m^F_i$ as follows:

$$d^* = \min_{\forall j} \frac{||\Delta m^F_i - \Delta m^T_j||}{||m^T_j||}, 1 \leq j \leq n^T \tag{4}$$

where $n^T$ is the total number of the training samples. The slice corresponding to the closest sample is then activated if $d^* \leq 0.35$. If it is a three-state slice, we activate its corresponding state. The slice reverts to idle at $t_j$ if $||m^C_j - \Delta q^{-1}_{k,j} \cdot m^C_k \cdot \Delta q_{k,j}||$, where $k$ is $i - l^D$, is less than $||m^C_j - \Delta q^{-1}_{i,j} \cdot m^C_i \cdot \Delta q_{i,j}||$. This condition ensures that $m^C_j$ has a similar value with that obtained at $t_k$, i.e., before activating the slice.

It should be noted that MagPie slices have discrete input states (idle and active) but also support an additional virtual state, called an active-and-hold state, for continuous inputs. Once a slice is activated, it transitions into the state until explicitly deactivated. This addition allows MagPie to support continuous controls, such as adjusting volume and zooming, which are integral to smartphone usability.

**Simple one-time calibration.** Before enabling BoD interaction on a smartphone, MagPie conducts a user-involved calibration consisting of three steps:

- **Layout registration.** Users register a MagPie layout, which they will use, through a graphical user interface as shown in Figure 8 by freely mapping specific slices to desired positions.
- **Training set creation.** After layout registration, users are asked to collect a set of training data for the layout by triggering each slice 5–10 times in comfortable poses. For each input, MagPie extracts its signature as described above and uses it as a training sample ($\Delta m^T_i$). We then set the input detection threshold ($\theta^T$) empirically as $0.8 \times \min^{n^T}_{i=1} ||\Delta m^T_i||$. This entire process, which takes under a minute, is needed only once for each layout. This is thanks to the capability of MagPie to discard the effect of smartphone orientation and environmental noise on magnetometer readings and thus extract environment-independent and time-invariant signatures. Note that we can further reduce the burden for training data collection by sharing training samples between layouts if they use the same type of slices on the same positions.

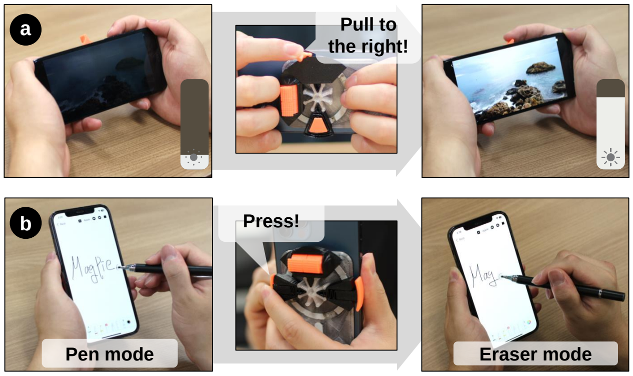



**Figure 9: Application scenarios of MagPie. (a) Click-away adjustment of screen brightness while watching video clips. Users can gradually increase or decrease the brightness by continuously pulling the sLever to the left or right. (b) Uninterrupted note-taking through simultaneous use of a touchscreen (for handwriting) and MagPie (for pen/eraser mode switching).**

- **Sensor calibration.** Users are instructed to move their smartphone in a figure-eight motion for a few seconds to collect magnetometer data, which is used to compute the initial inference parameters ($a_0^S$ and $b_0^H$) via an ellipsoid fitting algorithm [31]. This manual sensor calibration is required when newly attaching the MagPie accessory or changing layouts. The parameters, however, may lose accuracy in long-term use due to changes in surrounding magnetic environments. In this case, MagPie automatically updates them with the help of commercial mobile platforms, including iOS and Android, which support periodic magnetometer calibration [4, 14].

## 5 MagPie Implementation

We develop a hardware and software prototype of MagPie as a MagSafe accessory and a library for iOS and Android applications. The accessory consists of low-cost components, including a base frame and slices (printed with PETG filaments using a Bambu Lab X1-Carbon 3D printer), a MagSafe magnet ring, and iron plates. Its total manufacturing cost is less than 4 USD. Note that we confirmed that the 3D-printed components have high durability, reliably handling over 10,000 inputs in real-world environments. Durability could be further enhanced by using flexible materials such as nylon. Once the accessory is attached to a smartphone, MagPie tracks magnetic field variations using the smartphone's built-in magnetometer and gyroscope at a sampling rate of 100 Hz and identifies MagPie inputs via our proposed magnetic sensing method.

### 5.1 MagPie Applications

MagPie with its reconfigurable design encourages the development of more user-friendly and innovative applications. In light of this, we have implemented diverse smartphone applications that provide enhanced or even unique user experiences with MagPie. These include game, video player, camera, and note-taking applications.

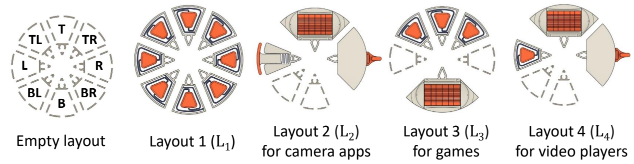



**Figure 10: MagPie layouts used for experiments. A slice with dotted lines represents an empty slot in a base frame.**

**Tangible BoD gamepads.** MagPie turns the back of a smartphone into a tangible game controller. For instance, an rLever can serve as a directional pad for side-scrolling games, while rButtons handle in-game actions (see Figure 1(d)). This BoD gamepad eliminates the need for on-screen virtual buttons, freeing up display space and allowing players to use more than just their thumbs during gameplay. Additionally, MagPie enables smartphones to act as remote game controllers. Imagine someone who plays mobile games on a larger screen via screen sharing. With the tangible design of MagPie that provides tactile feedback, he no longer needs to look at his smartphone to find buttons, enabling more immersive gameplay experiences.

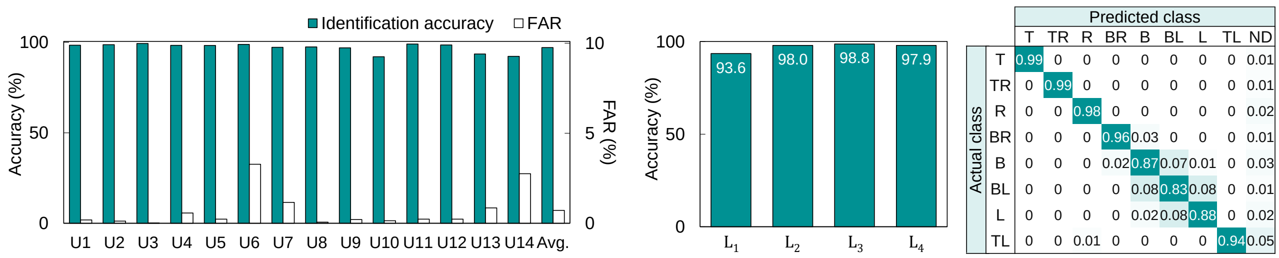
**Click-away video player control.** Adjusting settings like brightness during video playback can severely disrupt viewing experience on legacy smartphones. For example, iPhone users should open Control Center by swiping down from the top-right corner of the screen, and then increase or decrease the brightness. During this time, the entire video screen is covered by the center. With MagPie, users can easily adjust the screen brightness by just attaching an sLever slice and pulling it left or right without covering the screen (see Figure 9(a)). Furthermore, they can add more slices to handle diverse functions in the video player, such as fast forward and rewind.

**Camera interfaces for one-handed use.** Modern camera applications offer numerous features, from just taking a photo to changing a lens, zooming in and out, focusing on objects, and switching shooting modes. However, fully utilizing these features often requires both hands, limiting usability in one-handed scenarios, such as when carrying luggage. MagPie addresses this by enabling users to customize the combination of MagPie slices for one-handed use and map them to specific camera functionalities as demonstrated in Figure 1(d).

**Uninterrupted note-taking via simultaneous use of touch and BoD interfaces.** Note-taking on smartphones often requires users to pause to adjust tools or navigate menus, disrupting the workflow. With MagPie, the users can avoid these interruptions with the collaborative use of touch and BoD interfaces. For example, as illustrated in Figure 9(b), they can switch to eraser mode by simply pressing an sButton slice while handwriting on the touchscreen. This simultaneous use opens up such new multitasking scenarios, which can improve both usability and efficiency of note-taking applications.

## 6 Microbenchmarks

In this section, we verify the design of MagPie in terms of accuracy, usability, deployability, and robustness through experiments with




(a) Over different users.

(b) On diverse layouts.

(c) Confusion matrix for identification accuracy on $L_1$.

**Figure 11: Overall identification accuracy of MagPie. Note that in (c), each class denotes the attachment location of its corresponding slice, while 'ND' denotes inputs not detected by MagPie.**

real-world users. The benchmark experiment and the user studies in Section 7 were approved by the Institutional Review Board (IRB) of the institution to which the primary authors are affiliated.

## 6.1 Methodology

We conducted experiments with 14 participants (8 males and 6 females) from our university. They, aged 20 to 28, were selected since they are one of the most active smartphone users. All experiments were performed in a controlled classroom environment to minimize magnetic field fluctuations caused by electronic devices and user movements. During the entire experiment, we utilized an iPhone 12 smartphone running iOS 17.6 with four MagPie layouts ($L_1$ – $L_4$), as depicted in Figure 10. Specifically, $L_1$ is modeled for situations where the maximum number of MagPie slices (i.e., eight rButtons) are used. On the other hand, $L_2$ – $L_4$ layouts are tailored to camera, game, and video player applications, respectively, mentioned in Section 5.1. The participants were required to maintain specific orientation and holding styles according to the application scenario. For instance, they kept a right-handed use in portrait mode for $L_2$ while using $L_3$ and $L_4$ in landscape mode with both hands. In the case of $L_1$, which does not match a certain real-world scenario, the participants were instructed to use it freely without adhering to specific settings. Be aware that the layout for the note-taking application scenario, discussed in Section 5.1, was not included in the microbenchmark experiments as it shares similar configurations with $L_2$.

In these experiments, the participants initially performed layout registration and sensor calibration once per layout, followed by making 50 inputs for each slice (100 for three-state slices due to their two input mechanisms). During that time, we simultaneously collected sensor streams using the smartphone's built-in magnetometer and gyroscope with a sampling rate of 100 Hz and extracted the magnetic signature of each input using our proposed input detection method. For evaluation, we constructed a training data set by randomly selecting 10 signatures per slice and used the rest as a test set. This process was repeated 100 times for each layout.

Unless otherwise specified, we conducted all the microbenchmark tests with the default setup discussed above.

**Metrics.** We verify the performance of MagPie using the following metrics:

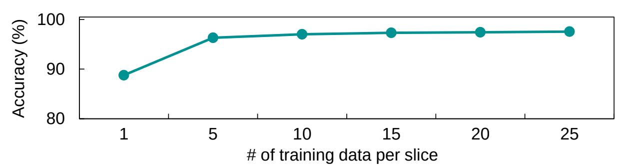


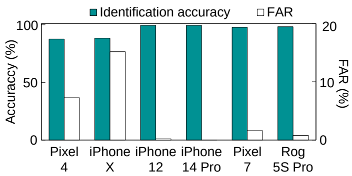

**Figure 12: Impact of calibration efforts. Note that each calibration process can be done within one minute.**

- *Identification accuracy.* We define the identification accuracy as the ratio of the number of successfully identified MagPie inputs to the number of total inputs.
- *False Activation Rate (FAR).* The false activation is defined as the event that noise is mistakenly identified as a MagPie input. We then measure FAR, i.e., how often false activation occurs while using MagPie, as the ratio of the number of false activation events to the number of total inputs.

## 6.2 Overall performance of MagPie

MagPie achieves high identification accuracy (97.1% on average) and low FAR (0.7% on average) regardless of users (see Figure 11(a)). This is thanks to the easy-to-use design of MagPie. For example, we observed that most of the participants could make MagPie inputs effortlessly using their fingers placed in the back of the smartphone. While users (e.g., U10 and U14) with smaller hands than average faced challenges in using MagPie, especially with layouts containing many slices (e.g., $L_1$), MagPie still delivers reasonable identification accuracy (> 93.6%). The accuracy could be further improved in real-world use cases via the reconfigurable design of MagPie to allow users to customize layouts based on their hand size and smartphone holding style.

Figure 11(b) illustrates that MagPie precisely identifies user inputs on diverse layouts with different slice configurations. On $L_1$, which has the maximum number of MagPie slices, identification accuracy slightly drops because inputs made on the slices located far from a smartphone's magnetometer have similar magnetic signatures as observed in Section 3.2. Therefore, as demonstrated in Figure 11(c), MagPie fails to accurately distinguish the inputs for the slices attached to the locations 'B', 'BL', and 'L'. However, except these locations, MagPie keeps high accuracy inputs because it




(a) Over different smartphone models.

| Actual class \ Predicted class | T | TR | R | BR | B | BL | L | TL | ND |
|---|---|---|---|---|---|---|---|---|---|
| T | 0.81 | 0.1 | 0.05 | 0.02 | 0 | 0 | 0 | 0.01 | 0.01 |
| TR | 0.11 | 0.86 | 0.01 | 0.01 | 0 | 0 | 0 | 0 | 0.01 |
| R | 0.04 | 0.01 | 0.77 | 0.17 | 0 | 0 | 0 | 0 | 0.01 |
| BR | 0.02 | 0.01 | 0.19 | 0.77 | 0 | 0 | 0 | 0 | 0.01 |
| B | 0 | 0 | 0 | 0 | 0.99 | 0 | 0 | 0 | 0.01 |
| BL | 0 | 0 | 0 | 0 | 0 | 0.98 | 0 | 0 | 0.02 |
| L | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| TL | 0.01 | 0 | 0 | 0 | 0 | 0 | 0 | 0.98 | 0.01 |

(b) Confusion matrix of identification accuracy using $L_1$ on Google Pixel 4.

**Figure 13: Impact of smartphone form factors.**

maintains at least 45-degree spacing between ferromagnetic plates present in slices and thus ensures unique magnetic signatures from each slice. This indicates that MagPie can provide users with fluent vocabulary by combining various kinds of slices.

**Impact of the number of training data.** MagPie requires users to collect training data when a layout is newly registered. Therefore, to enhance usability, it is essential to minimize a user's training effort. As shown in Figure 12, identification accuracy remains above 96.3% even with just five training data per slice. Increasing the number of training data improves the accuracy but slightly, demonstrating that a simple one-minute calibration is sufficient to convert the back of a smartphone into an interaction space.

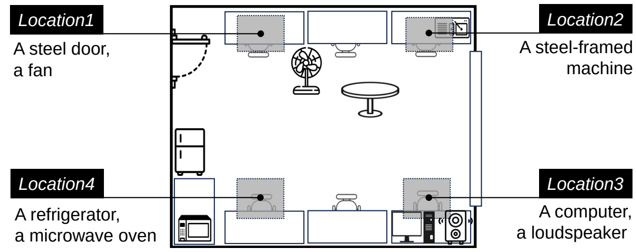
**Response time.** We measured the time elapsed to handle each MagPie input (1,000 times in total) to verify how fast MagPie can provide feedback to user inputs. The experiment results confirmed that MagPie processes quite efficiently, with an average response time of 5.87 ms. This is significantly faster than the minimum responsiveness required for user-interactive applications (e.g., a latency of 100 ms) [30].

**Battery consumption.** We evaluated MagPie 's energy overhead on Android, as it provides more detailed battery usage information compared to other platforms. Using a Google Pixel 4, we measured power consumption over 30 minutes under two conditions: displaying a blank screen at 50% brightness with no applications running, and the same setup with MagPie running in the background. To simulate intensive usage, MagPie inputs were repeatedly triggered, mimicking scenarios like button mashing in gameplay. Each experiment was repeated five times. Results showed that MagPie increased battery consumption by 32 mAh, a negligible impact given the smartphone's 2800 mAh capacity.

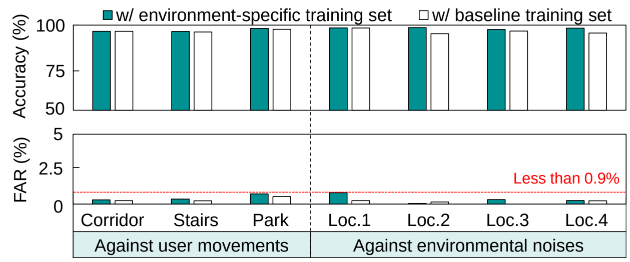
## 6.3 Robustness of MagPie

We carried out further experiments with 5 real-world users to assess the robustness of MagPie. In more detail, we designed experiments to evaluate the effectiveness of MagPie under various conditions, encompassing different devices, user movement variations, and environmental changes. It is worth noting that all these robustness experiments were conducted on the layout $L_4$, assuming a realistic scenario where users are watching videos in diverse conditions.

**Against device variations.** We examine the effect of smartphone form factors on the performance of MagPie using six different smartphones (Apple iPhone X, iPhone 12, iPhone 14 Pro, Goole




(a) Locations and their magnetic noise sources.




(b) Robustness of MagPie.

**Figure 14: Robustness experiment setups and results.**

Pixel 4 (Pixel 4), Google Pixel 7 (Pixel 7), and Asus Rog 5s Pro (Rog 5s Pro)). Among these, iPhone X, Pixel 4, Pixel 7, and Rog 5s Pro are not MagSafe-enabled smartphones. So, we used a MagSafe-like case designed for the smartphones to snap MagPie onto the devices.

As shown in Figure 13(a), MagPie performs well on iPhone 12 and iPhone 14 Pro with native MagSafe support. For example, it achieves an identification accuracy of 99.5% and an FAR of 0.1% even on the large-sized smartphone (iPhone 14 Pro). Similarly, on non-Apple devices such as Pixel 7 and Rog 5s Pro, MagPie provides high identification accuracy (above 97.8%) and low FAR (below 1.6%). However, MagPie struggles on Pixel 4 and iPhone X as their magnetometer is placed at the left- or right-center side. This placement causes two problems. First, the magnetometer readings vary significantly even with subtle movements, e.g., incomplete pressing, on the slices located too near the sensor, resulting in a considerable increase in FAR. Second, identification accuracy decreases because inputs from slices on the opposite side of the magnetometer produce weaker magnetic variations and thus have less-discernible signatures. For example, on Pixel 4 with the layout $L_1$, the accuracy drops by 22.9 percentage points for MagPie inputs made at the farthest location from the magnetometer ('R') compared to those at 'L' (see Figure 13(b)). Note that as discussed in Section 6.2, similar accuracy drops are observed in MagSafe-enabled devices, but at different locations than Pixel 4 due to differences in magnetometer placement. A potential solution to mitigate these issues is to provide a device-specific instruction for layout configuration. For example, given a smartphone's magnetometer location, MagPie could identify less-effective areas for BoD interaction and guide users to avoid placing multiple slices in those regions.

**Against magnetic noise.** MagPie, as a magnetic interface, is susceptible to magnetic noise from user movements and environmental

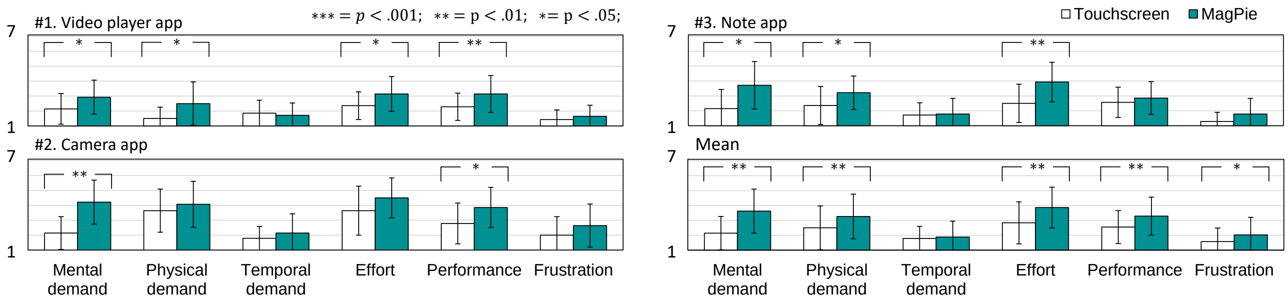



**Figure 15: NASA-TLX results and the effect of customizable layouts of MagPie. The Wilcoxon Signed-rank test was used to test the statistical significance at the 5% levels.**

variations. To verify its robustness, we conducted the following experiments:

- *User movement noise experiments.* Participants used MagPie while walking outdoors (a park) and indoors (a corridor and a stairs).
- *Environmental noise experiments.* Participants used MagPie at four locations in an office room, each with different magnetic noise sources as shown in Figure 14(a).

In this robustness test, we also evaluate the usability of MagPie by measuring its performance with two different training sets; *i*) *a baseline training set* collected in the default environment described in Section 6.1 and *ii*) *an environment-specific training set* collected in the target environment.

Figure 14(b) illustrates that MagPie maintains high performance even under noise, achieving identification accuracy above 95.8% with a negligible number of false activation events. This robustness comes from the noise reduction techniques used in MagPie, such as sensor-fused magnetic noise cancellation [12] and user-involved or automatic magnetometer calibration (details in Section 4.2). These methods also help extracting environment-independent signatures by filtering environment-specific interference noise, thus enabling MagPie to offer high accuracy without requiring additional training data for the given environment. For example, MagPie achieves an average identification accuracy of 97.2% with the baseline training set. This confirms that training data collection is needed only once per layout during registration, thereby enhancing usability.

## 7 User Studies

We conducted user studies with two objectives: 1) Study 1: To evaluate user experience with applications using MagPie, and 2) Study 2: To evaluate user experience with the processes required for using MagPie (e.g., calibration, button registration). A total of 14 participants (7 males and 7 females) participated in Study 1. Among them, 11 participants (6 males and 5 females) who were interested in MagPie 's reconfigurability also participated in Study 2. The participants were recruited from a local university, with an average age of 22.07 years (SD = 2.79). All participants had over three years of smartphone experience and were familiar with smartphone usage. Only individuals who had not participated in the microbenchmark experiment were eligible for these user studies. Each participant was compensated with $15. It should be noted that we also conducted a comparison study between MagPie and the touchscreen interface in terms of task completion time during gameplay. This additional study result is provided in the Appendix for reference, as they are supplementary to the primary findings discussed here.

### 7.1 Study 1: Evaluating Usability of MagPie Applications in Everyday Tasks

The primary goal of this study is to validate a potential of MagPie as a practical solution. To this end, we assessed the usability of MagPie in comparison to touchscreens, widely regarded as the gold standard for smartphone interaction, across diverse application scenarios.

**Task and experiment design.** In the experiment, we provided video player, camera, and note-taking scenarios described in Section 5. For each scenario, we developed three new applications to enable input using MagPie as well as a touchscreen. For a fair comparison, the applications using the touchscreen interface were designed to be operated in a way that closely resembles the interaction methods used in everyday life. Specifically, participants conducted given tasks in three different scenarios as follows:

- *Video player scenario.* Participants were asked to play and pause videos, adjust screen brightness, and seek specific scenes with $L_4$ in Figure 10. The fast-forward and rewind functions were assigned to the rLever, play/pause to the rButton, and brightness adjustment to the sLever. Participants operated the video player application in landscape orientation, using both hands to control the interfaces.
- *Camera scenario.* Participants were instructed to zoom in and out, switch between video and photo modes, toggle between front and rear cameras, and take pictures with $L_2$ in Figure 10. The layout included an sButton for capturing, an sLever for mode switching and camera direction toggle, and an rLever for zooming in and out. Participants operated the device in portrait orientation with one hand.
- *Note-taking scenario.* Participants were instructed to write, erase, undo/redo, change pen types, and adjust thickness using a modified version of $L_2$ in Figure 10, where the sLever at the 'R' position was replaced with an sButton. The layout included an rLever for adjusting pen thickness, an sButton on the right for undo, and another sButton on the left for toggling pen mode (e.g.,

erasing/writing). Participants operated the device in portrait orientation, holding it with one hand and using a capacitive stylus with the other.

**Procedure.** The studies were conducted in the order of video player, camera, and note-taking scenarios. In each scenario, participants first interacted with the touchscreen interface to operate the provided application and then switched to the MagPie interface. Initially, we provided our predefined MagPie interface layout to participants as described above. Subsequently, we explained the customizability of MagPie to users and offered the opportunity to freely customize the interface. This allowed participants to adjust the position of each module as desired and selectively allocate only the necessary functions, enabling them to create their own personalized interface configuration. At the end of each scenario, participants answered a NASA-TLX [17] survey with a 7-point Likert Scale to assess the workload caused by MagPie and the touchscreen, and they evaluated the overall usability of MagPie after all of the scenarios.

**Result.** Figure 15 summarizes the NASA-TLX survey results for each application scenario. Note that the Wilcoxon Signed-rank test is used to assess the statistical significance as the data are not normally distributed. Across all scenarios, users reported higher mental demand when using MagPie ($z$ = -2.43, -2.96, -2,47, and $p$ < .05, < .001, < .05 for video player, camera, and note app, respectively). In addition, on average, MagPie was found to require a higher workload in the physical demand ($z$ = -2.67, $p$ < .01) and effort ($z$ = -2.83, $p$ < .01) metrics. These results may be attributed to the unfamiliarity of MagPie compared to touchscreens. For example, P4 stated, *"I've never used an accessory attached to the back of a smartphone before, so it feels a bit awkward."* Despite this, many participants found usability comparable in some aspects, such as temporal demand ($z$ = -0.71 and $p$ = 0.48 on average), and they positively evaluated MagPie 's overall usability in the post-survey, particularly appreciating its *shortcut* functionality.

As shown in Figure 16, most of the participants responded positively to the questions regarding ease of learning (5.86 on average (SD=1.23) in Q2), intuitive design (5.35 on average (SD=1.22) in Q3), and occlusion issue (5.92 on average (SD=1.05) in Q5). P11 commented, *"The operations of the slices were intuitive, making it easy to use."*, and P14 remarked, *"Operating tactile buttons on a mobile device was intriguing, and it became more convenient as I became accustomed to it."* However, for the question about convenience (Q1), 29% of participants responded disagree or somewhat disagree. In the interview, P5 and P9 stated, *"Because my hands are small, the more slices are attached, the worse the grip comfort becomes."*. Also, P6 and P7 mentioned, "It was difficult to operate when too many modules are attached." These responses increase the need for more ergonomic design of MagPie slices.

Moreover, participants also commented on their evaluations of each scenario. Among them, in the camera scenario where the mobile device had to be operated with one hand, the users especially highly evaluated the usability of MagPie. P3 responded, *"It was convenient to use the desired functions with one hand in the camera scenario,"* and P7 responded, *"It was intuitive because the actual actions and functions such as zooming in/out or shooting using the sButton on the camera were well-matched."* The participants also mentioned the benefits of BoD interactions, such as avoiding screen

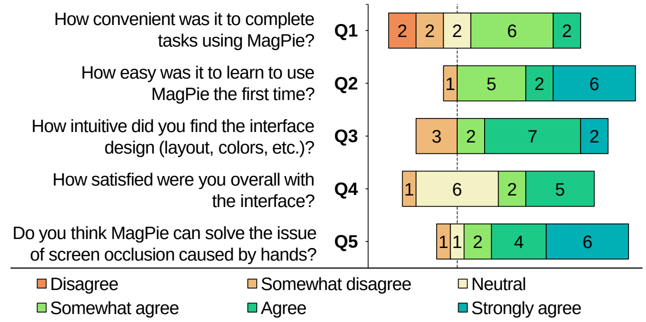



**Figure 16: Post-survey results on Usability of MagPie. Note that no responses were given for *Strongly disagree* in any question, so this category is not displayed in the legend.**

occlusion and providing shortcuts. P10 and P14 commented, *"It was good that the input could be transmitted without the problem of covering the screen."* In particular, P10 responded, *"While watching videos or taking notes, it was beneficial that MagPie could use specific functions immediately without needing to activate a control center."* P14 also mentioned in terms of interest that the operation principles and methods of using MagPie were fun.

Especially, the intriguing point to the participants was the fact that the layout was reconfigurable. After completing each scenario using the predefined layout we provided, we allowed participants to modify the layout as desired. They tried to adjust the layout by moving the position of slices or reducing the number of slices. P9, who mentioned discomfort due to hand size, said, *"Control became much more comfortable after customizing the layout."* P7 and P9 stated, *"Excluding slices that make it uncomfortable to hold, the usability is satisfying."* Additionally, P6 and P11 noted, *"Moving the position of modules that felt uncomfortable greatly improved the user experience."* These findings indicate that MagPie's customizable design, which allows users to tailor the interface to their needs and preferences, can significantly reduce workload and increase usability.

## 7.2 Study 2: Evaluating Layout Registration and Reconfiguration Process of MagPie

We conducted an additional study to evaluate first-users' experiences during the layout registration and reconfiguration processes required to use MagPie. A total of 11 participants (6 males and 5 females) volunteered for this study, and they were compensated with $10.

**Task and experiment design.** The study provided three potential scenarios for using MagPie:

- *Layout registration.* Participants, as first-time users, were asked to register the $L_2$ layout for using the camera app(see Figure 10). The setup and registration process consists of *i*) attaching MagPie slices to the base frame for configuring the target layout, *ii*) registering the layout via MagPie configuration application, *iii*) performing an eight-figure motion for sensor calibration, and *iv*) collecting training data for individual slices.

| | Scenario #1 | | Scenario #2 | | Scenario #3 | |
|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD |
| Q1 - How fast could you complete the setup processes? | 4.00 | 1.34 | 5.45 | 0.82 | 6.36 | 0.67 |
| Q2 - How convenient were the setup processes? | 3.82 | 1.54 | 5.27 | 1.01 | 6.55 | 0.52 |

**Table 1: Survey results from Study 2. Each rating was collected in a 7-point Likert Scale after the completion of each scenario.**

- *Layout reconfiguration.* After the first scenario, the participants could modify the layout of modules based on their preferences. After that, they registered the reconfigured layout.
- *Layout reuse.* Assuming users with prior experience, the participants were asked to simply reuse a previously registered layout. For the reuse, they just performed the first and third tasks of the layout registration process.

**Procedure.** Participants were briefed on the registration process and followed on-screen instructions for the setup.

We provided the scenarios in order, starting from the first scenario assuming a first-time user, to the third scenario assuming a user with prior experience. After completing each scenario, participants rated the setup process by rating its perceived duration and convenience using a 7-point Likert scale. We opted to survey perceived time and convenience rather than measuring actual execution time or completion rates to focus more on investigating the user experience. Additionally, we performed follow-up interviews to receive detailed feedback from the participants.

**Result.** Table 1 presents the survey results for each scenario. In Scenario 1, where participants encountered the registration process for the first time, the ratings of 4.0 for speed (Q1) and 3.82 for convenience (Q2) reflect the challenges of learning a new system. Some participants reported that the training data collection process felt lengthy. For instance, P13 stated, *"Collecting training data five or ten times felt repetitive and long. Although the process itself is straightforward, it gives the impression that the overall process is longer than it actually is."*

In Scenario 2, ratings increased by 1.45 points. This improvement can be attributed to two main factors. First, 72.7% of participants retained some slices from their previous layouts when configuring a new layout based on personal preferences, reducing training data collection as explained in Section 4.2. Second, the same percentage of participants reported better familiarity with the registration process after completing it once, making the setup more intuitive. For instance, P4 stated, *"The setup process itself is not difficult, so I was able to understand and perform the registration steps easily."*

In Scenario 3, where participants reused a previously saved layout, ratings further improved, with the highest scores observed (6.4 for Q1, 6.5 for Q2). This reflects the benefits of having pre-collected training data for input recognition and prior layout configuration, requiring only accessory attachment and sensor calibration for immediate use with minimal effort. These findings indicate that the effort required for the preliminary setup of MagPie may decrease further with repeated use.

In summary, when first using MagPie, participants felt that the process of collecting training data was somewhat lengthy (P2, 9, 13). However, they responded that the registration process itself was easy to learn and not particularly burdensome (P2, 3, 4, 6, 8, 10, 11, 13). Notably, once a specific layout was registered and reused, participants reported that the time required to start using MagPie became significantly shorter (P3, 10, 11).

However, approximately 45.5% of participants reported that the sensor calibration process slightly detracted from the overall convenience of the MagPie's registration process. The most common sentiment among participants who found the calibration inconvenient was that *"Performing this motion every time the layout is changed feels tiresome to users."*. This feedback highlights an area for potential improvement in simplifying the calibration step to further enhance the user experience. Additionally, some participants suggested that the registration process could be further streamlined by enabling the system to automatically recognize the layout configuration during the slice attachment phase. For example, P14 noted, *"It would be much more convenient if the system could instantly recognize the slice upon attachment and be ready to use right away"*. We consider adding distinctive patterns at the slice connection points to address these needs, enabling automatic slice recognition through unique sounds or vibrations and enhancing the user experience.

## 8 Limitation and Future Work

**Enhancing robustness to extremely heavy noise.** MagPie may experience malfunctions in extremely noisy environments, such as in elevators, electric vehicles, and subways, despite the use of noise cancellation techniques. One possible solution involves incorporating additional features robust to magnetic field distortions, such as subtle motions caused when using MagPie slices. We leave this as our future work.

**Consideration of long-term magnetic field impacts.** Prolonged exposure to magnetic fields can cause smartphone malfunctions, such as repeated IMU recalibration or interference with optical image stabilization. To minimize these effects, MagPie strictly adheres to MagSafe accessory guidelines [3] by using small ferromagnetic plates that generate no additional magnetic fields and ensuring stable magnetic conditions before and after BoD interaction. However, frequent magnetic field fluctuations over long periods may still pose risks. Therefore, it is essential to conduct a long-term evaluation of how MagPie might impact the smartphone components, which we will address in future work.

**Simultaneous use with other MagSafe accessories.** MagSafe's structural constraints allow only one accessory to be attached to a smartphone at a time. Since our system is also designed as a MagSafe accessory, it is subject to the same limitation. However, we anticipate that if accessories such as wallets or holders are designed as MagPie slices, it would be possible to use them in conjunction with our proposed input slices. Additionally, a MagPie base frame can be expanded to include features such as wireless charging. We plan to explore this potential expansion in future work.

**Enhancing input recognition algorithm.** The current MagPie prototype is designed with the assumption that users will trigger one slice at a time with the appropriate force. However, during our user study, we observed counterintuitive cases where a small number of participants triggered multiple slices simultaneously or pressed buttons incompletely. Such input styles could cause the magnetic fields from multiple slices to interfere with each other or incomplete inputs to form false-positive magnetic fields, resulting in input recognition errors. To address these edge cases, we plan to complement the current input recognition algorithm by incorporating additional modalities, such as acoustic signals, as part of our future work. For example, we can extend MagPie's mechanical structure to generate sounds at different frequencies for each slice position when completely triggered and leverage these sounds as additional modalities to distinguish slice inputs.

**Exploration of more ergonomic slice design.** As discussed in Section 7.1, although the customizable nature of MagPie allows users to optimize their comfort and ease of use, participant feedback revealed that some bulky slices can still create negative experiences despite this flexibility. For example, P2 and P14 stated, *"Large slices like 'rLever' cause discomfort regardless of their placement."*. Thus, we plan to address this limitation in future work by developing more compact and ergonomic slice designs.

## 9 Conclusion

This paper presents MagPie, an innovative interface that extends the dimensions of smartphone interaction to the back of the device, while satisfying the following requirements: high deployability, usability, safety, responsiveness, accuracy, and robustness. To realize this, MagPie harnesses the magnetic phenomena induced by MagSafe. Specifically, it is designed as a customizable tangible input accessory that snaps onto any MagSafe-enabled smartphone, empowering users to tailor its input modules (MagPie slices) as desired and providing tactile user feedback during interactions. These slices have a unique structure that converts mechanical inputs into magnetic signals. The signals are then detected using the smartphone's built-in magnetometer and used as a key feature for identifying MagPie inputs. Through the evaluation with a prototype implementation of MagPie, we demonstrated that MagPie can identify inputs with a high level of accuracy *i*) regardless of users, smartphone form factors, and layouts and *ii*) even in magnetically-noisy environments. Furthermore, through in-depth user studies with 14 participants, we also demonstrated that MagPie's intuitive and tangible design allows users to quickly get adapted to BoD interaction, while its customizable design drastically reduces users' perceived workload. Overall, the participants offered positive feedback. We anticipate that MagPie will accelerate the development of creative and useful applications in the near future.

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## References


[1] Heba Abdelnasser, Ayman Khalafallah, and Moustafa Yousef. 2018. MagController: A System for Touchless Mobile Devices Control Using the Magnetic Field. In *2018 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops)*. IEEE, Piscataway, NJ, USA, 300–305. doi:10.1109/PERCOMW.2018.8480128

[2] Takehiro Abe and Daisuke Sakamoto. 2021. MagneTrack: Magnetic Field Separation Method for Continuous and Simultaneous 1-DOF Tracking of Two-magnets. In *Proceedings of the 23rd International Conference on Mobile Human-Computer Interaction* (Toulouse & Virtual, France) *(MobileHCI '21)*. Association for Computing Machinery, New York, NY, USA, Article 1, 11 pages. doi:10.1145/3447526.3472052

[3] Apple Inc. 2023. Accessory Design Guidelines for Apple Devices (R21). https://developer.apple.com/accessories/Accessory-Design-Guidelines.pdf. Retrieved: November 30, 2023.

[4] Apple Inc. 2024. CMCalibratedMagneticField. https://developer.apple.com/documentation/coremotion/cmcalibratedmagneticfield. Retrieved: January 24, 2024.

[5] Daniel Ashbrook, Patrick Baudisch, and Sean White. 2011. Nenya: subtle and eyes-free mobile input with a magnetically-tracked finger ring. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI '11)*. Association for Computing Machinery, New York, NY, USA, 2043–2046. doi:10.1145/1978942.1979238

[6] Lonni Besançon, Mehdi Ammi, and Tobias Isenberg. 2017. Pressure-Based Gain Factor Control for Mobile 3D Interaction using Locally-Coupled Devices. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 1831–1842. doi:10.1145/3025453.3025890

[7] Alex Butler, Shahram Izadi, and Steve Hodges. 2008. SideSight: multi-"touch" interaction around small devices. In *Proceedings of the 21st Annual ACM Symposium on User Interface Software and Technology* (Monterey, CA, USA) *(UIST '08)*. Association for Computing Machinery, New York, NY, USA, 201–204. doi:10.1145/1449715.1449746

[8] Ke-Yu Chen, Kent Lyons, Sean White, and Shwetak Patel. 2013. uTrack: 3D input using two magnetic sensors. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology* (St. Andrews, Scotland, United Kingdom) *(UIST '13)*. Association for Computing Machinery, New York, NY, USA, 237–244. doi:10.1145/2501988.2502035

[9] Liang Chen, Dongyi Chen, and Zhizhong Tan. 2020. Fingertip-Specific Mobile Interaction Through Camera-Based Fingertip Identification. *Journal of Physics: Conference Series* 1673 (2020), 012046.

[10] Victor Cheung and Audrey Girouard. 2019. Tangible Around-Device Interaction Using Rotatory Gestures with a Magnetic Ring. In *Proceedings of the 21st International Conference on Human-Computer Interaction with Mobile Devices and Services* (Taipei, Taiwan) *(MobileHCI '19)*. Association for Computing Machinery, New York, NY, USA, Article 26, 8 pages. doi:10.1145/3338286.3340137

[11] Stefano Chioccarello, Arthur Sluÿters, Alberto Testolin, Jean Vanderdonckt, and Sébastien Lambot. 2023. FORTE: Few Samples for Recognizing Hand Gestures with a Smartphone-attached Radar. *Proc. ACM Hum.-Comput. Interact.* 7, EICS, Article 179 (June 2023), 25 pages. doi:10.1145/3593231

[12] Jaemin Choi, Insu Kim, and Hyosu Kim. 2024. MagID: Enhancing the Functionality of Off-the-Shelf Smartphones Through Magnetic Accessory Identification. *IEEE Access* 12 (2024), 149903–149915. doi:10.1109/ACCESS.2024.3474915

[13] Rajkumar Darbar, Prasanta Kr. Sen, Punyashlok Dash, and Debasis Samanta. 2016. Using Hall Effect Sensors for 3D Space Text Entry on Smartwatches. *Procedia Computer Science* 84 (2016), 79–85.

[14] Google. 2024. Position sensors. https://developer.android.com/develop/sensors-and-location/sensors/sensors_position#sensors-pos-mag. Retrieved: February 9, 2025.

[15] Emilio Granell and Luis A. Leiva. 2017. $\beta$Tap: back-of-device tap input with built-in sensors. In *Proceedings of the 19th International Conference on Human-Computer Interaction with Mobile Devices and Services* (Vienna, Austria) *(MobileHCI '17)*. Association for Computing Machinery, New York, NY, USA, Article 52, 6 pages. doi:10.1145/3098279.3125440

[16] Chris Harrison and Scott E. Hudson. 2010. Minput: enabling interaction on small mobile devices with high-precision, low-cost, multipoint optical tracking. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Atlanta, Georgia, USA) *(CHI '10)*. Association for Computing Machinery, New York, NY, USA, 1661–1664. doi:10.1145/1753326.1753574

[17] Sandra G Hart. 2006. NASA-task load index (NASA-TLX); 20 years later. In *Proceedings of the human factors and ergonomics society annual meeting*. Sage publications Sage CA: Los Angeles, CA, Sage Publications, Los Angeles, CA, USA, 904–908.

[18] Eiji Hayashi, Jaime Lien, Nicholas Gillian, Leonardo Giusti, Dave Weber, Jin Yamanaka, Lauren Bedal, and Ivan Poupyrev. 2021. RadarNet: Efficient Gesture Recognition Technique Utilizing a Miniature Radar Sensor. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 5,

14 pages. doi:10.1145/3411764.3445367

[19] Sungjae Hwang, Myungwook Ahn, and Kwang-yun Wohn. 2013. MagGetz: customizable passive tangible controllers on and around conventional mobile devices. In *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology* (St. Andrews, Scotland, United Kingdom) *(UIST '13)*. Association for Computing Machinery, New York, NY, USA, 411–416. doi:10.1145/2501988.2501991

[20] Yan-Bin Jia. 2008. Quaternions and rotations. *Com S* 477, 577 (2008), 15.

[21] Kleomenis Katevas, Hamed Haddadi, and Laurissa Tokarchuk. 2016. SensingKit: Evaluating the Sensor Power Consumption in iOS Devices. In *Proceedings of the 2016 12th International Conference on Intelligent Environments (IE)*. IEEE, London, UK, 222–225. doi:10.1109/IE.2016.50

[22] Hamed Ketabdar, Mehran Roshandel, and Kamer Ali Yüksel. 2010. Towards using embedded magnetic field sensor for around mobile device 3D interaction. In *Proceedings of the 12th International Conference on Human Computer Interaction with Mobile Devices and Services* (Lisbon, Portugal) *(MobileHCI '10)*. Association for Computing Machinery, New York, NY, USA, 153–156. doi:10.1145/1851600.1851626

[23] Bogyeong Kim, Chaeeun Lee, Jung Huh, and Woohun Lee. 2020. Puppet Book: Digital Storybook with Back-of-Device Puppeteering Interface for Parent and Child. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI EA '20)*. Association for Computing Machinery, New York, NY, USA, 1–4. doi:10.1145/3334480.3383175

[24] Hwan Kim, Yea-kyung Row, and Geehyuk Lee. 2012. Back keyboard: a physical keyboard on backside of mobile phone using qwerty. In *CHI '12 Extended Abstracts on Human Factors in Computing Systems* (Austin, Texas, USA) *(CHI EA '12)*. Association for Computing Machinery, New York, NY, USA, 1583–1588. doi:10.1145/2212776.2223676

[25] Sven Kratz and Michael Rohs. 2009. HoverFlow: expanding the design space of around-device interaction. In *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services* (Bonn, Germany) *(MobileHCI '09)*. Association for Computing Machinery, New York, NY, USA, Article 4, 8 pages. doi:10.1145/1613858.1613864

[26] Jess McIntosh, Paul Strohmeier, Jarrod Knibbe, Sebastian Boring, and Kasper Hornbæk. 2019. Magnetips: Combining Fingertip Tracking and Haptic Feedback for Around-Device Interaction. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. doi:10.1145/3290605.3300638

[27] Seyed Ahmadreza Mousavi and Rastko Selmic. 2023. Wearable Smart Rings for Multifinger Gesture Recognition Using Supervised Learning. *IEEE Transactions on Instrumentation and Measurement* 72 (2023), 1–12.

[28] Inc. Mouser Electronics. 2024. HPL Hall Effect Pushbutton Switches. https://www.mouser.com/new/otto/OTTOHPL/. Retrieved: September 10, 2024.

[29] Inc. Mouser Electronics. 2024. JHL Large Hall Effect Joystick. https://www.mouser.com/new/otto/otto-jhl-hall-effect-joystick/. Retrieved: September 10, 2024.

[30] Jakob Nielsen. 1993. Response Times: The 3 Important Limits. https://https://www.nngroup.com/articles/response-times-3-important-limits/. Retrieved: March 15, 2024.

[31] Talat Ozyagcilar. 2012. Calibrating an ecompass in the presence of hard and soft-iron interference. *Freescale Semiconductor Ltd* (2012), 1–17.

[32] Keunwoo Park, Daehwa Kim, Seongkook Heo, and Geehyuk Lee. 2020. MagTouch: Robust Finger Identification for a Smartwatch Using a Magnet Ring and a Built-in Magnetometer. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. doi:10.1145/3313831.3376234

[33] Maximilian Schrapel, Florian Herzog, Steffen Ryll, and Michael Rohs. 2020. Watch my Painting: The Back of the Hand as a Drawing Space for Smartwatches. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI EA '20)*. Association for Computing Machinery, New York, NY, USA, 1–10. doi:10.1145/3334480.3383040

[34] James Scott, Shahram Izadi, Leila Sadat Rezai, Dominika Ruszkowski, Xiaojun Bi, and Ravin Balakrishnan. 2010. RearType: Text Entry Using Keys on the Back of a Device. In *Proceedings of the 12th International Conference on Human Computer Interaction with Mobile Devices and Services*. Association for Computing Machinery, New York, NY, USA, 171–180.

[35] Masanori Sugimoto and Keiichi Hiroki. 2006. HybridTouch: an intuitive manipulation technique for PDAs using their front and rear surfaces. In *Proceedings of the 8th Conference on Human-Computer Interaction with Mobile Devices and Services* (Helsinki, Finland) *(MobileHCI '06)*. Association for Computing Machinery, New York, NY, USA, 137–140. doi:10.1145/1152215.1152243

[36] Ke Sun, Ting Zhao, Wei Wang, and Lei Xie. 2018. VSkin: Sensing Touch Gestures on Surfaces of Mobile Devices Using Acoustic Signals. In *Proceedings of the 24th Annual International Conference on Mobile Computing and Networking* (New Delhi, India) *(MobiCom '18)*. Association for Computing Machinery, New York, NY, USA, 591–605. doi:10.1145/3241539.3241568

[37] Taichi Tsuchida, Kazuyuki Fujita, Kaori Ikematsu, Sayan Sarcar, Kazuki Takashima, and Yoshifumi Kitamura. 2022. TetraForce: A Magnetic-Based Interface Enabling Pressure Force and Shear Force Input Applied to Front and Back of a Smartphone. *Proc. ACM Hum.-Comput. Interact.* 6, ISS (2022), 22 pages.

[38] Lei Wang, Xiang Zhang, Yuanshuang Jiang, Yong Zhang, Chenren Xu, Ruiyang Gao, and Daqing Zhang. 2021. Watching Your Phone's Back: Gesture Recognition by Sensing Acoustical Structure-Borne Propagation. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 5, 2 (2021), 26 pages.

[39] Daniel Wigdor, Clifton Forlines, Patrick Baudisch, John Barnwell, and Chia Shen. 2007. Lucid touch: a see-through mobile device. In *Proceedings of the 20th Annual ACM Symposium on User Interface Software and Technology* (Newport, Rhode Island, USA) *(UIST '07)*. Association for Computing Machinery, New York, NY, USA, 269–278. doi:10.1145/1294211.1294259

[40] Wireless Power Consortium. 2024. Wireless Power Consortium Website. https://www.wirelesspowerconsortium.com/. Retrieved: January 24, 2024.

[41] Pui Chung Wong, Hongbo Fu, and Kening Zhu. 2016. Back-Mirror: back-of-device one-handed interaction on smartphones. In *SIGGRAPH ASIA 2016 Mobile Graphics and Interactive Applications* (Macau) *(SA '16)*. Association for Computing Machinery, New York, NY, USA, Article 10, 5 pages. doi:10.1145/2999508.2999522

[42] Chang Xiao, Karl Bayer, Changxi Zheng, and Shree K. Nayar. 2019. Vidgets: Modular Mechanical Widgets for Mobile Devices. *ACM Trans. Graph.* 38, 4 (2019), 12 pages.

[43] Chang Xiao, Karl Bayer, Changxi Zheng, and Shree K. Nayar. 2021. BackTrack: 2D Back-of-device Interaction Through Front Touchscreen. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 7, 8 pages. doi:10.1145/3411764.3445374

[44] Xiang Xiao, Teng Han, and Jingtao Wang. 2013. LensGesture: augmenting mobile interactions with back-of-device finger gestures. In *Proceedings of the 15th ACM on International Conference on Multimodal Interaction* (Sydney, Australia) *(ICMI '13)*. Association for Computing Machinery, New York, NY, USA, 287–294. doi:10.1145/2522848.2522850

[45] Amit Yadav, Alexander Keith Eady, Sara Nabil, and Audrey Girouard. 2019. JoyHolder: Tangible Back-of-Device Mobile Interactions. In *Proceedings of the 2019 ACM International Conference on Interactive Surfaces and Spaces* (Daejeon, Republic of Korea) *(ISS '19)*. Association for Computing Machinery, New York, NY, USA, 343–346. doi:10.1145/3343055.3360748

[46] Wataru Yamada, Hiroyuki Manabe, and Daizo Ikeda. 2018. CamTrackPoint: Camera-Based Pointing Stick Using Transmitted Light through Finger. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 313–320. doi:10.1145/3242587.3242641

[47] Frederick J. Young. 1968. Ferromagnetic Shielding Related to the Physical Properties of Iron. In *1968 IEEE Electromagnetic Compatibility Symposium Record*. IEEE, Piscataway, NJ, USA, 88–95. doi:10.1109/TEMC.1968.4307123

[48] Cheng Zhang, Anhong Guo, Dingtian Zhang, Caleb Southern, Rosa Arriaga, and Gregory Abowd. 2015. BeyondTouch: Extending the Input Language with Built-in Sensors on Commodity Smartphones. In *Proceedings of the 20th International Conference on Intelligent User Interfaces* (Atlanta, Georgia, USA) *(IUI '15)*. Association for Computing Machinery, New York, NY, USA, 67–77. doi:10.1145/2678025.2701374

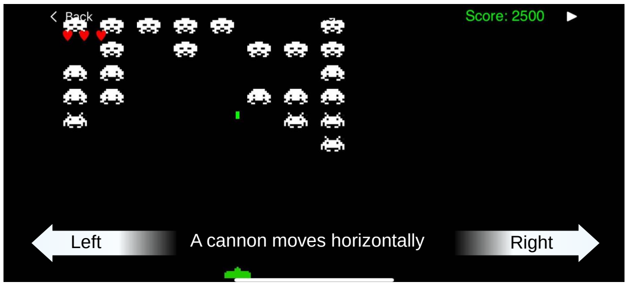
[49] Cheng Zhang, Aman Parnami, Caleb Southern, Edison Thomaz, Gabriel Reyes, Rosa Arriaga, and Gregory D. Abowd. 2013. BackTap: robust four-point tapping on the back of an off-the-shelf smartphone. In *Adjunct Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology* (St. Andrews, Scotland, United Kingdom) *(UIST '13 Adjunct)*. Association for Computing Machinery, New York, NY, USA, 111–112. doi:10.1145/2508468.2514735

[50] Chi Zhang, Deepak Ranjan Sahoo, Jennifer Pearson, Simon Robinson, Mark D Holton, Philip Hopkins, and Matt Jones. 2020. Active PinScreen: Exploring Spatio-Temporal Tactile Feedbackfor Multi-Finger Interaction. In *22nd International Conference on Human-Computer Interaction with Mobile Devices and Services* (Oldenburg, Germany) *(MobileHCI '20)*. Association for Computing Machinery, New York, NY, USA, Article 18, 11 pages. doi:10.1145/3379503.3403531

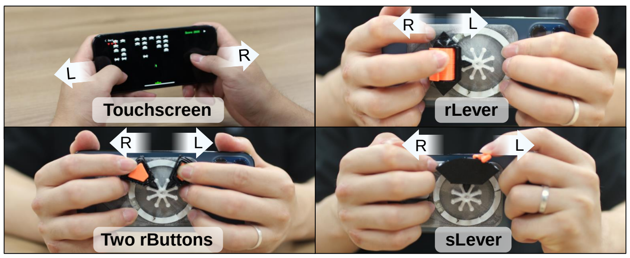
# A Supplementary study: Task Performance Comparison Across Interfaces

**Task.** In this study, we compared task performance between MagPie and a touchscreen interface, using task completion time as the representative performance metric. For the task, we utilized an open-source game called `Space Invaders`[4], where the objective was to eliminate all enemies as quickly as possible by moving a laser cannon horizontally and firing lasers at them (see Figure 17(a)).

[4] https://github.com/ChoiysApple/Space-Invaders




(a) Screenshot of `Space Invaders`.




(b) Gameplay examples with different interfaces.

**Figure 17: Experiment setups for task performance comparison with real-world users.**

Since the lasers fired continuously and automatically, participants only needed to control the cannon, moving it left or right. We then asked each participant to play the game using the touchscreen interface and MagPie, while holding the smartphone in a horizontal orientation.

As demonstrated in Figure 17(b), when using the touchscreen interface, participants moved the cannon by touching the far edges of the display with both thumbs. A discrete touch caused the cannon to move once, while holding down the touch enabled continuous movement in one direction. Additionally, we modified the game to support the MagPie interface. The cannon's movement direction and distance were determined by which MagPie slice is activated and for how long, respectively. To control the potential confounding variables (e.g., cannon control sensitivity and enemy movement speed), all game configurations were kept consistent across interfaces. For example, the distance the cannon moved when the screen was touched for 1 second was identical to the distance it moved when the MagPie slice was activated for the same duration.

**Experiment design.** For the MagPie interface, we used three distinct layouts, each involving 1) two rButtons, 2) an rLever, and 3) an sLever (see Figure 17(b)). Therefore, a task set consisted of four conditions: one using the touchscreen interface and three using the different MagPie layouts. In each task set, participants played the game until they completed the game (i.e., remove all enemies) under each of the four conditions and repeated the task set three times. Thus, a total of 12 tasks (4 conditions $\times$ 3 sets) were performed per participant. To minimize potential learning effects that occurred by the order of the conditions, we randomized the order within each set using a Balanced Latin Square design.

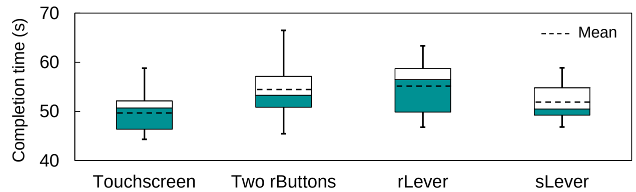



**Figure 18: Task completion time comparison between different interfaces. In this box-and-whisker plot, the whiskers indicate the minimum and maximum completion times, respectively.**

**Procedure.** Participants were given a one-minute practice session prior to their first trial with each interface, allowing them to familiarize themselves with the specific input modality. This practice also allowed participants to become familiar with game specifications such as input sensitivity and the moving speed of enemies. During the experiment, participants were instructed to eliminate all enemies as quickly as possible by either touching the screen or using the MagPie slices. We measured the time taken from when the participant started the game until the task was completed. The completion time was automatically recorded within the game.

**Result.** Figure 18 illustrates the completion times of the `Space Invaders` task using touchscreen and MagPie interfaces. Although all participants used MagPie for the first time and were much more familiar with the touchscreen interface, MagPie showed a comparable to or slightly lower performance than the touchscreen. The mean completion time for the touchscreen interface was 49.53 seconds (SD=3.99), and the completion times for the MagPie interfaces, using two rButtons, rLever, and sLever, were 54.56 seconds (SD=5.75), 55.32 seconds (SD=5.52), and 51.9 seconds (SD=4.01), respectively. Interestingly, the minimum completion time across all types of interfaces was similar. The touchscreen interface resulted in 44.31 seconds, the two rButtons layout 45.45 seconds, the rLever 46.78 seconds, and the sLever 46.82 seconds. This indicates that participants who quickly adapted to MagPie could complete the tasks within nearly equivalent time to using the touchscreen. In other words, we confirmed that MagPie has an intuitive design, allowing users to quickly understand how to operate it effectively with minimal learning time. One notable point is that, as shown in Figure 18, the distribution of completion times for the two rButtons interface was noticeably wider compared to the other interfaces. This wider distribution could be caused by several participants who reported that pressing the button required more effort than expected. For example, *P13* mentioned, *"Pressing the button required more physical effort than I expected."*. Given this feedback, as a potential solution, we can reduce the spring tension which could alleviate the physical strain and improve the usability.