Bendy: Exploring Mobile Gaming with Flexible Devices

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ABSTRACT
We explore the use of bend gestures in gaming with flexible devices and investigate the size differences between smartphones and tablets. We conducted a study asking users to select bend gestures for nine tasks derived from gaming, grouped by navigation, action, and deformation. Our results suggest pairing opposing tasks, such as navigating left and right, by gesture location. We saw low consensus for action tasks, and strong association between the location of the gestures and the location of the visual, relating to the Simon Effect. We suggest guidelines for the design of game controls for flexible devices. We implemented the proposed gestures into six games using an interactive flexible prototype in our second study. Our results are similar between sizes, yet with an overall user preference for the smaller prototype. We observed that hand positioning is an important usability issue to consider when designing flexible devices.

Keywords
Deformable user interface; deformable prototype; flexible display; bend gestures; mobile games

ACM Classification Keywords
H.5.2 [Information interfaces and presentation]: User Interfaces.

INTRODUCTION
We use deformation to interact with everyday objects, allowing for a rich set of possibilities involving many degrees of freedom with intuitive interactions [27]. Flexible devices benefit from these attributes by connecting reality based interactions with virtual experiences, which embody engaging interactions [7–9]. This element of embodied engagement is a natural fit for games on mobile devices, which are hampered to engage by touch-only interactions.

Mobile games are designed to be short, simple and competitively engaging, which makes them the most used mobile application [31]. However, there are limitations due to small screen sizes such as the use of on-screen game controls and finger occlusion [33], an inherent issue of touch input. By leveraging the use of deformation as an input method and the success of mobile games, we envision an input modality that could potentially create new and innovative gameplay. In addition, we view bend interactions to complement touch input as well as potentially resolve its limitations. While deformable interactions may offer many new creative possibilities, we begin our exploration through the use of simple binary bend gestures with basic gaming tasks inspired by classic arcade games.

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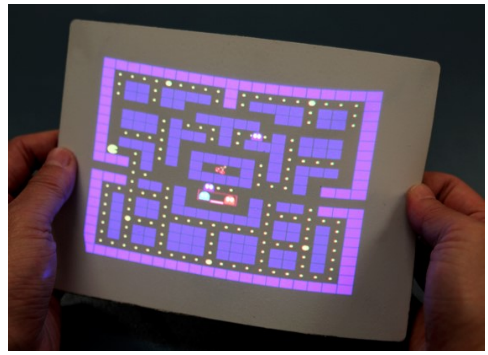

Figure 1. Bendy explores bend gestures for novel game input. The user plays Pacman by bending the flexible prototype.

We present an explorative study into the interactions of mobile gaming using an interactive flexible prototype called Bendy (Figure 1). We aim to understand and explore the use of bend gestures when playing games on a flexible device. This work contributes to deformable interactions research in two folds: an analysis of bend gestures for gaming, and a qualitative examination of user experiences in gaming with a flexible prototype. We also examine differences between two common mobile sizes: smartphones and small tablets.

We conducted a study where participants were presented with a series of simple game tasks and asked to select a bend gesture for each. We quantified and used the results to inform the design of the bend gestures for six simple games. We built the Bendy prototype to provide users with an interactive experience and gathered feedback regarding their user experience and the usability of the bend gestures. We conclude by reporting insights found and propose guidelines for designing games with mobile flexible devices.

RELATED WORK
We surveyed deformable interaction research, and mobile game input modalities.

Deformable Interactions
Deformable user interfaces use the physical deformation of an object as a form of input [12], ranging from simple bends

[25,30] to complex deformations [11,12]. Lahey et al. [14] defined bend gestures as the "physical, manual deformation of a display surface to form a curvature for triggering an action on a computer display". Ahmaniemi et al. [1] suggested that their full potential occurs when they are mapped to continuous, bipolar input. The authors note that some discrete actions such as page turning also have strong value when performed with bends. They found bending to be well-suited for clearly-directional manipulations. Researchers have applied flexible devices to applications such as ebook readers [35,36], smartphones [14,28], tablets [30], media players [12] or to perform music [32].

We only found four instances of deformation in games, two presenting concepts and two evaluating simple games. Cobra [38] introduced flexible displays in a gaming context through the use of bend gesture input. They proposed a portable system comprised of a shoulder-mounted pico-projector connected to a laptop, which recognized user input from the flexible device. Their preliminary exploration did not expand on game interactions and omitted a user evaluation. Similarly, Nguyen et al. created foam-based prototypes that capture local pressure points and deformation in BendID [20] and Softii [19]. They indicated using their prototype with a 3D racing game but provided no detail other than a picture. In terms of experimentation, Ahmaniemi et al. [1] included a task to control the vertical position of a moving ball, which they qualified as a simple game. They reported participants suggesting games as an area with potential for bend gestures. Daliri and Girouard [6] used a simple game task to evaluate visual feedback guides. Users moved a character along a four by four grid while eating fruits. Grounded in prior work, our research extends beyond conceptual exploration [19,20,38] or extremely simple games [1,6] and examines gaming with flexible devices in detail.

Mobile Game Input

The most popular game input on current mobile devices is touch, which has two common interaction problems: screen occlusion, which is created by fingers reaching for a target on a screen; and the "*fat fingers"* problem, which is the ambiguity of the selection point [33]. In addition, the small display size of mobile devices often limits game interaction, as it is restrictive to use on-screen game controls.

Several comparative studies have explored the use of other input modalities versus touch input. Zaman et al. [39] compared the use of touchscreen-based controls on the Apple iPhone versus physical controls on the Nintendo DS for the game Assassin's Creed. They found users' performance and preference were significantly higher when using physical buttons. This suggests that designers need to consider alternative input methods for touchscreen devices. Chehimi and Coulton [5] explored the use of accelerometers in a 3D space shooter game and found the response from users to be positive and intuitive. Browne and Anand [4] evaluated usability and user experience of a side-scrolling shooter game for the iPod Touch using three inputs: accelerometer, simulated touch button and touch gestures. Users preferred the accelerometer-based interface and it also exhibited the best performance measures. Browne and Anand recommend that the physical properties of gestures should be directly translated into the virtual properties. While using the accelerometer has been widely accepted, tilting or shaking the mobile device can obstruct the field of view. These works illustrate the necessity of exploring other input modalities, which offer ways of improving touch input's shortcomings.

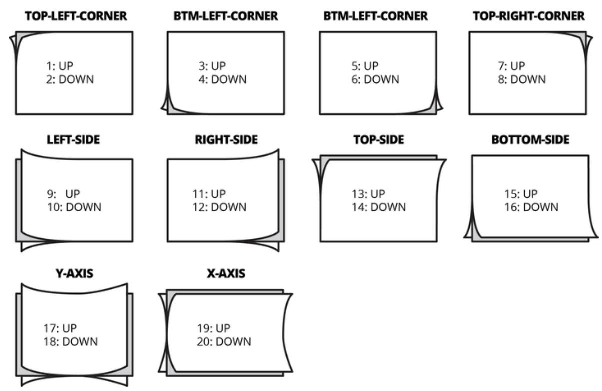

Figure 2. Bendy's bend gesture interaction language.

BENDY PROTOTYPE

We designed and built an interactive flexible prototype to investigate the use of twenty bend gestures with simple games. We used the fabrication technique for deformable prototypes outlined by Lo and Girouard [17]. To achieve our research goals, we assessed the requirements for the prototype based on size, material stiffness, and interaction.

Bend Gesture Interaction Language

Our interaction language uses the bend gesture classification scheme proposed by Warren et al. [34] involving location and direction. Gestures can be performed in ten locations using four corners, four sides, or along the x or y-axis in both directions, resulting in a set of twenty gestures (Figure 2). The nomenclature used in this paper to describe gestures first states the location and secondly the direction. The four corners are described as follows: *top-right, bottom-right, top-left or bottom-left corner*. Side bends are designated as *top, bottom, left or right side*. Central bends are described by the parallel axis of which they are bent. The *up* direction indicates a gesture performed toward the user and the *down* direction is performed away from the user.

Hardware and Apparatus

Bendy is comprised of three layers: a flexible plastic substrate, FlexPoint bidirectional bend sensors augmented with a flexible circuit, and a silicone enclosure (Figure 3, left). The prototype is cast in a material with a shore hardness of 30A, which is equivalent to a soft rubber gasket [22], as users feel more comfortable and engaged with less stiff materials [13]. This prototype has enough resilience to return to a neutral state after repeated deformations.

Researchers thus far have evaluated two sizes for flexible devices: smartphones [12,14] and large tablets [15,30], and

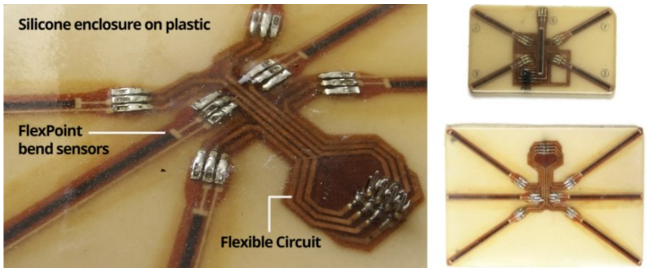

Figure 3. Bendy's three layers: the plastic substrate, the flexible circuit and the silicone enclosure.

prior work found small devices to be better than larger ones [16]. However, researchers have not studied sizes in between. As smartphones get bigger and tablets get smaller, we investigate the differences between smartphone, referred to as small (120 mm x 72 mm) and mini tablet size, called medium (170 mm x 120 mm), illustrated in Figure 3, right.

We simulated the display by projecting onto the surface of the prototype using a pico-projector. The animations in study one used the whole prototype, while the games were centered with a border of approximately 5 mm for the small prototype and 10 mm for medium prototype. We placed a fiducial marker on the back of the prototype and positioned a web camera to detect its location using reacTIVision [10]. We integrated this position data in the Processing applications to keep the projection within the frame of the prototype. We did not correct for the perspective deformation of the projection. Participants were asked to hold the prototype in front of the projector at a fixed distance. We adjusted the projector for each participant so that the display size remained consistent.

Sensors were strategically positioned for each prototype to detect the twenty bend gestures. There are four sensors in each four corners for both prototypes, two sensors centered on the left and right sides for the medium prototype, and one sensor horizontally in the middle of the small one. We detected gestures using the combination of activated sensors: corner bends required single sensor activation; top and bottom side bends required both corner sensors to be activated; left and right bends required all three sensors on that side to activate. We detected y-axis bends when all six sensors were activated, and the x-axis bends when only the four corner bends were activated.

We connected the sensors to an Arduino Uno microcontroller and implemented a digital smoothing algorithm to remove outliers. We set activation threshold values for every sensor so the angle for classifying a deformation as a bend would be approximately 30°. We sent the bend gesture output continuously to the Processing game applications. In Bendy, the gestures detected are binary in nature, that is each gesture is on or off, based on a threshold. However, they are in fact continuous; if users maintained the bend past the threshold, the system will recognize many gestures in a row. We used this bend gesture recognition in our second study. For our first study, bend gestures were recorded manually.

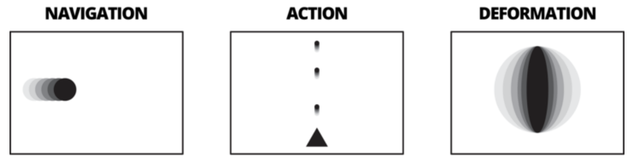

Figure 4. An example of our three gaming interactions.

STUDY 1: DECONSTRUCTING GAMING INTERACTIONS

Bend gestures are a novel interaction language for users and as a result, there are many intricacies to be examined. In the context of gaming, how would you navigate Mario and avoid enemies? What bend gestures would you use to shoot invading enemies? The main research goal of this study is to elicit bend gestures from users given these types of basic gaming interactions with our flexible prototype Bendy.

We conducted a study using simple gaming interactions represented by a simplified visual animation and asked users to select a bend gesture for each from our defined set of twenty (Figure 2). We simplified the graphic representation to remove visual bias. By using a simple *cause* and *effect* methodology, we observed user behaviours given the visual feedback (*effect)* of the system and asked users to select a bend gesture (*cause)*. This process provided a dialogue between the system and the behaviour enabling them.

We proposed a set of three tasks for each of three interaction categories: navigation, action, and deformation (Figure 4).

Navigation Tasks. We selected three navigation tasks to observe how participants would navigate on a 2D plane: left and right only, up and down only, and in all four directions. For the left/right and up/down tasks, we wanted to test if the location of the visual would influence the bend gesture performed. To investigate the relationship, we consider the stimulus-response compatibility principle, the Simon Effect [26]. Stimulus-response compatibility [23] is where the rate of information transfer is dependent on the association of stimulus and response. Simon found faster response times due to spatial correspondence, that is when the stimulus and response occur in the same location. For this task, the Simon Effect is relevant because the location of stimuli (visual) may influence the location of the response (gesture). We hypothesized that participants would select gestures relative to the location of the visual. Therefore, we used location as a variable condition for the left/right and up/down tasks. The visual was presented in three locations: top, center, bottom and left, center, right respectively. Within these tasks, we instructed participants that they could select gestures independently of each other, which meant they could repeat gestures should they see fit. The third navigation task combined all four directions and participants were asked to select four unique bend gestures. We designed this task to test how participants would map bend gestures given the condition they could not be collocated.

Action Tasks. We selected three tasks commonly found in gaming: shooting, jumping and rotating. This set of tasks represent a subset of arcade-style game actions that have no binding characteristics with respect to real-world deformable actions. We hypothesized that participants will have low consensus in transforming these tasks into bend gestures. In addition, participants were required to select separate bend gestures to navigate left and right. We included navigation in each task to test how participants would map action bend gestures given a situation where they could not be collocated with navigation bend gestures. These constraints reflect the constraints of real games. For example, a button on a game controller cannot move left and jump at the same time.

Deformation Tasks. We deviated from common game interactions and generated a set of three tasks embodying deformable characteristics found in real-world interactions, to leverage the properties of the flexible device. We devised a spring task where an object is pulled back and sprung forward by release, similarly to a catapult. The elasticity task explored compressing and stretching vertically and horizontally. This second task is like squeezing a sphere of soft material, such as a silicone ball or a water balloon. The final task manipulates magnitude by increasing and decreasing the size of an object. We hypothesized that these three tasks would achieve a higher level of consensus due to their relative closeness to real-world actions.

To summarize, we have made two hypotheses toward our research: (1) Participants will achieve a higher level of consensus if the tasks embody deformable characteristics and hold true for the converse and (2) the location of bend gestures will map relative to the location of the visual.

Participants

We recruited 24 participants (15 females) with an average age of 27.2 years old and were all right handed. Participants had no prior experience with bend gestures on flexible devices. Participants on average reported playing games occasionally (3.63/7) and had average gaming experience (3.54/7). Participants were given $10 compensation.

Methodology

In our pilot study, we observed participants were unsure of how to interact with the prototype. In addition, we expected our participants would be novice users. We iterated our study to include a short demonstration of the twenty bend gestures. As a result, participants were able to quickly grasp the full range of possible bend gestures and familiarize themselves with the prototype. We presented the nine tasks randomly and the conditions within each task were also at random. After viewing the visual, participants were asked to respond by performing a bend gesture. The researcher asked participants to repeat the bend gesture to confirm their decision. The researcher manually recorded the bend gestures selected. The procedure was repeated for both prototype sizes in a counterbalanced order.

Results

Each participant contributed 37 gestures for each prototype size for a total of 1,776 gestures. From the collected bend gestures, we calculated an agreement score [37], which represents the degree of consensus amongst participants. The value varies between 0 and 1, with a higher number indicating a stronger agreement. For example, for the navigation task, left, 15 participants chose left-side-down, 7 chose right-side-up, 1 chose top-left-corner-down and 1 chose top-right-corner-up. The agreement score for this task:

$$A_{left} = \left(\frac{15}{24}\right)^2 + \left(\frac{7}{24}\right)^2 + \left(\frac{1}{24}\right)^2 + \left(\frac{1}{24}\right)^2 = 0.48$$

The agreement scores are graphed in descending order for the medium prototype (Figure 5). In both sizes, the deformation tasks ranked the highest, whereas the action tasks ranked the lowest. Therefore, we omitted the graph for the small prototype. Table 1 summarizes the results for agreement score and the selected gesture for each task (i.e. the bend gesture with the largest frequency). We also identified tasks with conflicting results indicated by X. We define conflict as gestures that occur in equal frequencies or received a low agreement score ($A < 0.2$). Figure 6 illustrates the most selected and conflicting gestures for all tasks.

Navigation Tasks

(1) Up + Down. The most selected gesture sets are the same for both sizes. If the visual was located on either the right or left, participants mapped the gestures to the corners. When the visual was presented in the center, participants chose to bend the top-side-down to perform the up task. A conflict occurred in both sizes for the down task when the visual was in the center. Participants performed either the top-side-up or bottom-side-down gesture.

To evaluate for the Simon Effect, we complied the gestures per location: left, center, and right. We conducted a Chi-square test for association between the location of the gesture and visual location. We found a significant association between them for both sizes (small χ^2 (4) = 108.677, p < .001 and medium χ^2 (4) = 138.739, p < .001). Participants performed the gestures in the location of the visual stimuli.

(2) Left + Right. On the small prototype, participants selected to use the left and right sides down to perform navigate left and right, respectively. The location of the visual stimuli did not affect the gesture location.

The gestures performed on the medium prototype did not result in the same set. For the navigate left task, when the visual was in the bottom and center location, participants

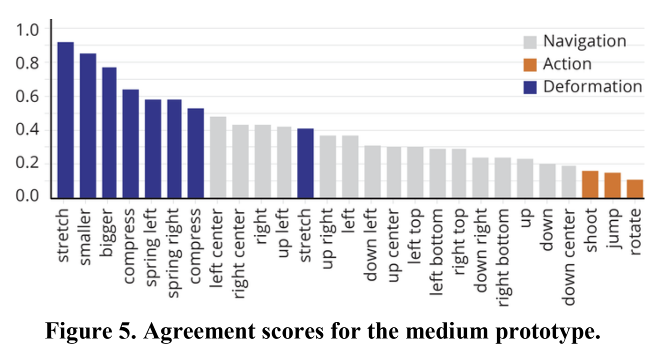

Figure 5. Agreement scores for the medium prototype.

Table 1. Agreement scores of both sizes and selected gesture represented by numbers in reference to Figure 2.

	Event	Variable	Agreement Small	Agreement Medium	Selected Small	Selected Medium
Navigation	down	center	0.25	0.19	X	X
		left	0.21	0.31	4	4
		right	0.28	0.24	6	6
	up	center	0.32	0.30	16	16
		left	0.27	0.42	2	2
		right	0.34	0.37	8	8
	left	bottom	0.32	0.29	10	10
		center	0.46	0.48	10	10
		top	0.28	0.30	10	2
	right	bottom	0.24	0.24	12	6
		center	0.46	0.43	12	12
		top	0.28	0.29	12	X
	down		0.20	0.20	15	X
	left		0.37	0.37	10	10
	right		0.42	0.43	12	12
	up		0.21	0.23	X	16
Action	rotate		0.15	0.11	X	X
	shoot		0.13	0.16	X	X
	jump		0.14	0.15	X	X
Deformable	spring	left	0.70	0.58	10	10
		right	0.70	0.58	12	12
	elasticity	hcompress	0.58	0.53	19	19
		vcompress	0.66	0.92	13	13
		hstretch	0.18	0.41	X	20
		vstretch	0.77	0.64	14	14
	magnitude	bigger	0.71	0.77	14	14
		smaller	0.78	0.85	13	13

selected to use left-side-down. When the visual was at the top, they selected top-left-corner-down. For the navigate right task, participants selected the bottom-right-corner-down when the visual was presented on the bottom. When the visual was presented at in the center participants choose right-side-down. A conflict occurred when the visual was presented in the top location. Participants equally selected top-right-corner-down or right-side-down.

We compiled the gestures performed according to location: top, center, and bottom and conducted the same Chi-square test. We found a significant association between the location of the gesture performed and visual stimulus location for both sizes (small χ^2 (4) = 33.222, p < .001 and medium χ^2 (4) = 90.937, p < .001). The significance found for the left/right task is unlike the one found in the up/down task. The association is regardless of the location of the visual, the gesture was performed in the center, which suggests using the using side bends to navigate left and right. While we did observe a slight difference with the medium prototype, a significant amount of gestures was still performed in the central location. This might suggest our results would not apply for much larger devices.

(3) 4-Way Navigation. For both sizes, the bend gestures for the left and right tasks are left-side-down and right-side-down. When it came to selecting gestures for the up and down tasks for both prototype, the conflict found earlier is also evident in this task. Participants struggled to reach a consensus whether to pair this task by location or direction.

Action Tasks

The agreement scores for all three action tasks ranked the lowest for both prototype and resulted in the largest number of unique gestures performed. There was no consensus for any gesture, though we noted a slight preference to map actions to the top-right-corner.

Deformation Tasks

(1) Spring. Both prototype sizes exhibited the same gesture-task pairings: the left side down gesture pulling the spring to the left. To manipulate the target line, participants used the top left-corner-down to move it up and the bottom-left-corner-down to move it down.

(2) Elasticity. Participants selected an x-axis gesture to compress/stretch an object along the horizontal axis and a y-axis gesture to compress/stretch along the vertical axis. Bend gestures for compression were performed in the up direction, and bend gestures for stretch were performed in the down direction. When asked to stretch the object on the small prototype along the horizontal axis, participants received a low agreement score value (0.18) as 10 participants performed the x-axis-down, and 9 participants performed y-axis-down.

(3) Magnitude. In both sizes, the bend gestures to increase and decrease the magnitude were y-axis-down and y-axis-up respectively.

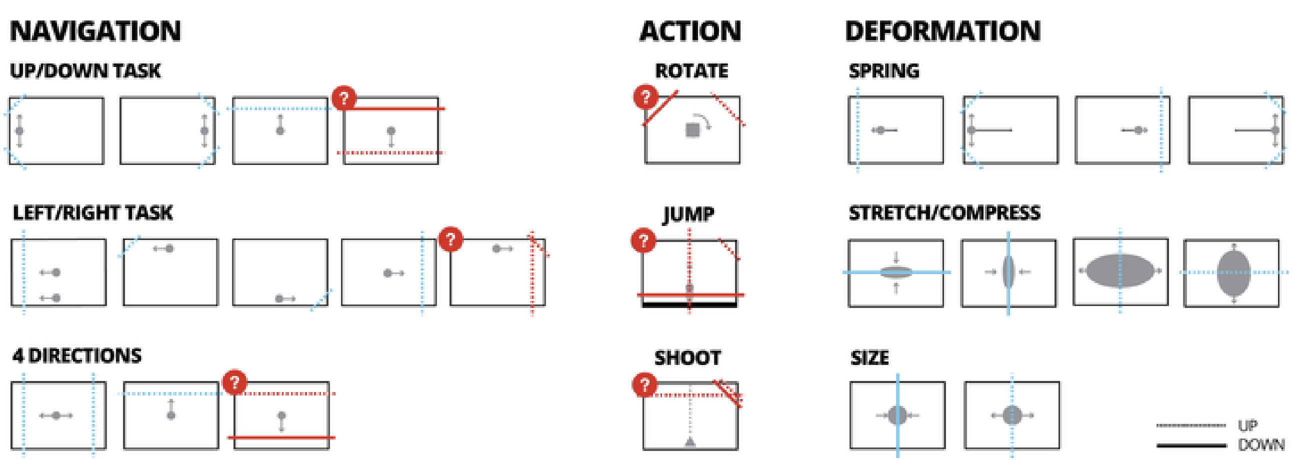

Figure 6. Most selected (blue) and conflicting (red) bend gestures for each task for medium prototype.

Discussion

We discuss our findings and suggest guidelines for designing gestures for gaming with flexible devices. Overall, we observed few differences in performance between the sizes.

Gestures for Navigation on a 2D Plane

Participants paired gestures with opposing tasks, a finding supported by prior work [14,25]. While we did not present the navigation tasks in pairs, most participants (85%) selected paired gestures by location. For instance, to go left and right, participants used the left and right side of the prototype. Only a few (4%) chose to pair gestures by direction: a few chose to move left and right by using only the right-side-up and right-side-down gestures.

In addition, participants demonstrated a common perception that governed how to move the virtual objects. They either "pushed" or "pulled" the object in the desired direction. For instance, a participant would use the left-side -down to "pull" the object to the left; whereas another participant might bend the right-side-up to "push" the object to the left. We analyzed the navigation tasks and observed 56% utilized the "pull" concept, whereas 25% performed the "push" concept, and the remaining 19% showed no particular pattern. We also observed that participants remained consistent in their responses once they perceived they were "pushing" the object, therefore inherently influencing how they selected bend gestures for subsequent tasks. For example, if a participant perceived to "pull" the object, they performed the down gesture in order to do so therefore most of their resulting gestures were in the down direction. Given these observations we suggest pairing opposing tasks by gesture location and using the down direction over up.

For the up/down tasks, participants performed the gesture in the stimulus location, which validates our hypothesis to be true and indeed adheres to the Simon Effect. While this holds true, during the study we observed that bending the prototype using the top and bottom sides were not only very awkward, but also required participants to reposition their hands. The combination of these observations presents an ergonomic concern for implementing the top and bottom side bends as gestures for gaming. In addition, we predict given the gaming context where time and challenge are a factor, performing these gestures would be unfavourable and lead to negative experiences. We suggest duplicating the gestures on both sides of the device to minimize the top/bottom side gestures. We tested this implementation in our second study.

For the left/right navigation task, the majority performed a central gesture. While we noticed that an increase in distance between visuals might compel users to the select gestures towards the visual's location (given the medium prototype's result), the evidence was not significant enough for us to implement into our design. We recommend for flexible devices that fall within our range in size to use the left and right side down for left/right navigation tasks. Our results support this finding as 45% of the gestures created for both sizes utilized these bends.

Gestures for Action Tasks

The action tasks ranked the lowest in user agreement and with the highest average of unique gestures performed. Our participants noted that these types of actions are dissimilar from deformable action and do not utilize the flexible properties of the device, which contributed to their inability to select a bend gesture. Despite participants having trouble to reach a consensus, we observed that many participants assimilated the top corners of the prototype to game console controls and would comment, "I would use it like a trigger button." In addition, several prior works note that the top corners are favourable for assigning frequent tasks [14]. For action tasks, we suggest assigning them to the top corners on both sides, maintaining symmetry, if this does not conflict with navigation gestures. Otherwise, we do not recommend assigning bends to such tasks.

Gestures for Deformation Tasks

Tasks that share deformable characteristics are easily translated into gestures for flexible devices (high user agreement and lowest number of gestures performed). Even for participants with no previous experience with flexible devices, selecting these gestures appeared effortless. Bending downward translated into increasing the surface of an object, while upwards mapped to decreasing.

We encourage designing games that leverage deformation, for example, stretching a bow to shoot targets, or flicking the device to hurl balls of paper into a trash can. The closer the interaction mimics a real-world deformable action, the easier it is for users to conceptualize and use the gestures.

STUDY 2: IMPLEMENTING BENDS IN ARCADE GAMES

We extend our exploration of gaming with flexible devices by further examining the gestures from the first study in an in-game context. We used the main findings from the first study and implemented the gestures with six games. We selected classic arcade-style games because of their simple game controls (e.g. navigation controls, rotation, sling, shoot), all of which could be done using binary input. We aimed to determine an overall preference for prototype size, evaluate the design of the game controls and observe behavioural patterns.

Games and Action Mapping

We used the results from the first study to guide our design for the game controls in this study using the following principles: use down gestures, pair opposing tasks by location, and map action tasks to the top-right-corner. We balanced each game to ease the play for the participant: the pace was decreased, and game life was unlimited to allow for sufficient opportunity for participants to experience the controls. Figure 7 illustrates the games and their bend gesture mapping.

The goal of Pong [2] is to return the ball to the opponent's side using a vertical right paddle. The researcher played using the keyboard to control the left paddle. We used the results from the up/down navigation task. The goal of Bricks [3] is to deflect the ball using a horizontal paddle and

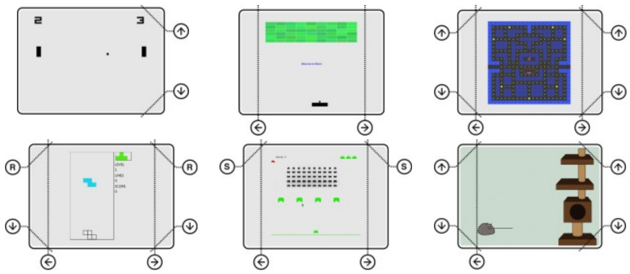

Figure 7. Games and their bend gesture mapping: Pong, Bricks, Pacman (top row), Tetris, Space Invaders, and Fat Cats (bottom row). Arrows indicate navigation actions, R indicates rotating the block and S indicates shooting.

eliminate the "bricks" above. We implemented the results suggesting the use of the central left and right side bends. In PacMan [18], the player navigates a character through a maze to eat all the pac dots, while avoiding the enemies. We identified navigating up/down to have usability concerns and therefore implemented the up/down tasks to the four corners to test how participants would fare using this mapping. Tetris [21] is a puzzle-based game where the user manipulates the position of the geometric shapes to form horizontal lines. In Space Invaders [29], the player controls a space ship by moving it horizontally, while shooting at the descending aliens above. For these two games, we remained consistent in assigning left and right side bends to navigate. We assigned the action task to the top right and left corners given the feedback from the first study that participants perceived the prototype to mimic that of a game controller.

Fat Cats was inspired by the popular game Angry Birds™ [24]. The objective of the game is to spring the cat toward the scratching post aiming for one of three target levels. We applied our results from the spring task and assigned the left-side-down gesture to launch the Fat Cat. Participants used the top and bottom corners down to move the target line.

Participants
We recruited 12 participants (4 females) with an average age of 24.3 years old with no prior experience with flexible devices. 10 participants were right handed, 1 left handed and 1 ambidextrous. We offered a $10 compensation. They reported playing games occasionally (4.51/7) and had an average gaming experience (4.08/7).

Methodology
We gave participants a brief introduction to flexible devices, bend gestures as input for gaming, and the prototype setup. To familiarize participants with the prototype, they completed a tutorial prior to playing the games. We designed a within-subjects experiment to evaluate perceptual differences between the two differently sized prototypes. The order of the six games was randomized and the prototype size was counterbalanced. Participants played each game until they reported confidence in evaluating the controls. We asked participants to rate the controls by indicating on a seven-point Likert scale (strongly disagree to strongly agree) given the statement "The controls were physically easy to perform". We also evaluated intuitiveness and asked them to rate the statement "The controls were mentally intuitive to use". To determine an overall preference for size, participants indicated their preference after each game and chose an overall size preference after playing all the games. We conducted a semi-structured interview and encouraged a "think out loud" protocol to solicit responses and gather additional insights regarding the user experience.

Results
We evaluated the user experience of gaming with flexible devices. We transcribed their responses and summarized them into descriptive codes. For example, the participant's comment "I like the smaller prototype because it was easier to grasp" would be translated to the codes: *small prototype* and *ergonomics*. This process was iterative until a finalized set reported the feedback gathered. We formulated the results from the second study and discuss our findings.

Preference for the Small Prototype
When asked to indicate their overall preference, 75% preferred using the small prototype. All participants commented on the distance between the controls and how it affected their performance. "The smaller one is better because the distance is closer, making them [controls] easier to access." (P9) The smaller distance enabled participants to "brace the entire device" (P4) and perform all the required gestures with minimal repositioning of the hands.

All four female participants reported the medium prototype to be more difficult to use due to having smaller hands. Three male participants indicated the medium one was "slightly more comfortable" because it fitted their hand size better. Overall, the small prototype provided a better user experience: it was easier to use and increased game performance.

Reducing Hand Repositioning to Perform Gestures
All participants commented on the repositioning of their hands to perform the gestures and preferred maintaining a close proximity to their grasp position. Almost all the participants (10/12) struggled with the game Pong and suggested the gestures be collocated by direction instead of location to reduce repositioning of the hands.

Observable Patterns of the Simon Effect
Our first study suggested for navigation tasks, there is a significant association between visual location and gesture location. Therefore, we implemented this finding into three games: PacMan, Tetris, and Space Invaders. Our implementation tested whether the Simon Effect would hold true if applied to games. For example, if PacMan was on the left, the participants would be more inclined to use the left top and bottom corners to move him up and down. In Tetris, if the puzzle piece was on the right, the participants would use the top right corner to rotate. Similarly, if the space ship in Space Invaders was on the left, participants would use the top-left-corner to shoot. However, we observed a very interesting pattern. All the participants used both sides of the prototype during PacMan, however, only some (7/12) during

Tetris and very few (3/12) during Space Invaders. During Space Invaders, half of the participants commented on the top-right-corner being similar to a game console controller: “It’s like using the buttons on my Xbox to shoot, which makes sense” (P7). It could be that the action of “shooting” as a repetitive trigger was easily relatable to the form factor of a flexible device. For future works, if the game tasks involve navigating in all four directions, the Simon Effect is indeed applicable. However, it should be carefully considered when designing other types of games.

Discussion

We implemented user-selected gestures as game controls and found overall positive results. Evaluating controls in this context allowed us to further uncover and extrapolate important insights that did not arise during the first study.

While the results from the first study strongly indicated that participants paired opposing tasks by location, the results of this study challenged this guideline, particularly for the up/down task in Pong. Pong received the most feedback, with participants suggesting to collocate the gestures to a single location for ease of use. Our evaluation proves to be beneficial in highlighting an important usability requirement: hand repositioning. While the result contradicts our suggested guideline, we may resolve the usability issue by increasing the size of the bend gesture and minimizing hand repositioning. The results also revealed user motivations whilst playing games that we did not account for previously. Because of the gaming nature, participants often expressed concern for performance and efficiency and that the game controls should not influence these two factors. This leads to interesting future work to see how game challenge would influence bend gestures. Overall, while this somewhat limits the validity of the first study, it mainly highlights the necessity to evaluate user-selected gestures in context.

In the second study, we observed participants using the deformable prototype like they would a game controller. As gestures were continuously generated while users were bending the prototype, participants tended to maintain the gesture in directional actions, similarly to holding the left side of the D-Pad to move left, while they naturally used more of a “flicking” motion to perform action tasks such as shooting or rotating a block. We found that participants did not use both sides of the display as often as we had expected. The Simon Effect appeared more prevalent in the navigation type game (e.g., PacMan) and less in the action games (e.g., Tetris and Space Invaders). This observation holds particularly true in the 2D shooter game where participants formed a strong association with the top-right-corner as the “trigger” button. It further strengthens participants strongly associate gaming with flexible devices to game controllers.

Limitations

Both studies were based on an explorative process and our hardware, software, and methodologies were designed to fit our goals. We were limited by technological feasibility in available hardware. In lieu of using a flexible display, we used projection. We made efforts to maintain the position of the display on the prototype, but we were unable to reduce distortion during bend interactions. We also do not know the influence of the border around the display on our results. In addition, the bend gesture recognition software used in the second study limited us to using binary controls, which we mitigated by choosing arcade-style games. While we outputted gestures continuously, hence our consideration of them as being continuous gestures, this still restricted the use of finer metrics. There is room to improve bend interaction sensing with higher-fidelity prototypes that use of the full potential of bend gestures [1], and an additional study with games using continuous controls is warranted.

CONCLUSION

With Bendy, we explored mobile gaming on flexible devices. We began our exploration by conducting a first study where users were asked to select bend gestures for tasks in three interaction categories: navigation, action, and deformation. Our results provided a set of bend gestures for the navigation and deformation tasks. We found that the action tasks scored lowest in user agreement and the deformation tasks ranked highest. Additionally, we compared two common mobile device sizes and found similar bend gestures were selected for each, leading us to suggest designers can select the same gestures for different size mobile devices (small and medium). Finally, we were interested in observing the Simon Effect with bend gestures and we found a strong association between the locations of the gesture and that of the visual stimuli. Our preliminary investigation also highlighted interesting interaction paradigms such as users pairing opposing tasks to gestures by location, “push” and “pull” mental models, and experimenting with various hand positions.

We evaluated Bendy using six simple arcade-style games that implemented the guidelines for our first study. We found participants preferring the small prototype due to increased ease of use and performance. We observed hand positioning as an important usability requirement to consider: participants were unanimously concerned with having to reposition their hands from their holding positions to perform bend gestures. Through two studies with the Bendy prototype, we show that the use of bend gestures for gaming with mobile devices is a novel and viable input modality.

To expand our work, we will explore additional gaming interactions using different flexible form factors and improved gesture recognition algorithms. Further works would include designing games using real-world metaphors, such as flicking a device to toss paper into a trash can. Finally, an evaluation of the combination of touch and bend is also warranted.

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