NailTactors: Eyes-Free Spatial Output Using a Nail-Mounted Tactor Array

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ABSTRACT

This paper investigates the feasibility of using a nail-mounted array of tactors, *NailTactors*, as an eyes-free output device. By rim-attached eccentric-rotating-mass (ERM) vibrators to artificial nails, miniature high-resolution tactile displays were realized as an eyes-free output device. To understand how to deliver rich signals to users for valid signal perception, three user studies were conducted. The results suggest that users can not only recognized absolute and relative directional cues, but also recognized numerical characters in EdgeWrite format with an overall 89% recognition rate. Experiments also identified the optimal placement of ERM actuators for maximizing information transfer.

Author Keywords

Nail-mounted device, tactor array, always-available output

ACM Classification Keywords

H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces

INTRODUCTION

Recently, wearable interface researchers have started placing always-available displays on users fingernails, because nail-mounted displays not only take advantages of enhancing touch interactions because of their wearing position [16], but also preserve the natural haptic feedback of skin without affecting native functions [3]. Previous studies have developed nail-mounted displays with visual displays or tactors. Visual displays such as NailDisplay [16] provide rich information in a high resolution, but are only available when users are visually engaged. For scenarios that require eyes-free touch inputs, such as in meetings, driving, or exercising, tactile displays [2] can communicate with users through tactile feedback, which is always available and more private than visual displays. However, since the single-vibrator vibrotactile output offered limited expressiveness and lack mnemonic properties [9], using single nail-mounted vibrator remains inefficient for the output of spatial or semantic information such as alphanumeric patterns.

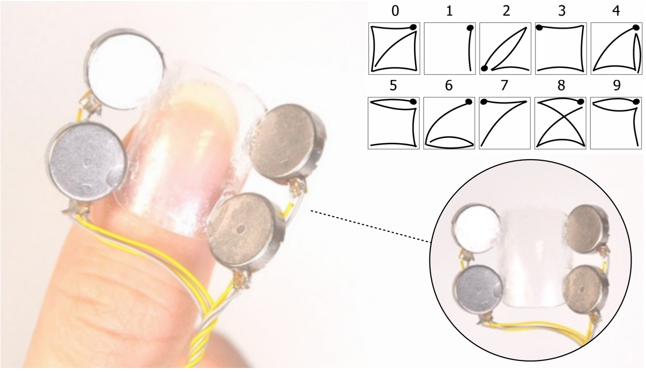


Figure 1. ***NailTactors*** **is a nail-mounted tactor array that can display numerical characters in EdgeWrite format.**

To increase the bandwidth of tactile communication, high-resolution tactile displays can be realized using an array of vibrators [8, 6], or specific mechanisms for creating 2D movements [12, 5, 9]. These high-resolution tactile displays can be attached to arbitrary body parts, such as a users wrist [8, 5] or back [6]. However, such devices are too bulky to be worn on the fingernails. Traxion [11] is an exceptional and lightweight single-tactor display based on an electromagnetic coil that provides clear 1D force feedback in two directions, but the provided information is limited to binary states.

This study investigated the feasibility of using a nail-mounted array of tactors, *NailTactors*, as an eyes-free output device. We realized several nail-mounted tactor displays by rim-attached rotating-mass vibrators that provide focused and clear vibrator signals on small contact areas. Then, three user studies were conducted to understand the effectiveness of information transformation using the implemented tactor arrays. Results of the first user study suggest that when the distance between the two vibration points is at least 12 mm, participants can recognize horizontal direction cues with more than 80% accuracy, and can differentiate their absolute positions. On the basis of these findings, a 2×2 tactor array was implemented, as shown in Figure 1. The results of the second user study suggest that users can identify the absolute position of vibration with 87.8% overall accuracy. Finally, we implemented EdgeWrite number patterns [19] on the 2×2 tactor array. The results of the third user study suggest that users can recognize the numerical patterns through the 2×2 tactor array with an overall accuracy of 89%. These experimental results suggest that placing a tactor arry on fingernails can effectively deliver eyes-free spatial cues and numerical information to users.

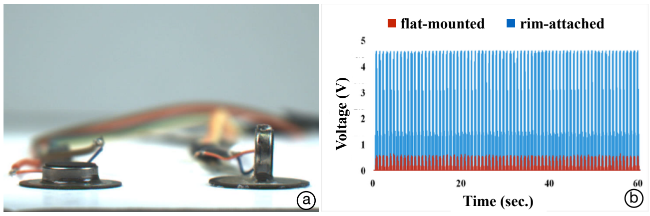


Figure 2. (a) Measuring vibration forces by fixing flat-mounted or erected eccentric-rotating-mass (ERM) vibrators on a pressure sensor. (b) Results show that the overall signal/noise ratios of rim-attached ERM vibrators are significantly higher than those of the flat-mounted ones.

DESIGN AND IMPLEMENTATION

Building Nail-Mounted Tactor Arrays

Eccentric-rotating-mass (ERM) actuators were selected in our implementation. The crucial component of an off-the-shelf disc-like actuator is an off-center rotating mass, which generates an omnidirectional vibration when it spins. To build a vibrotactile array, mounting ERM actuators by simply patching it onto the nail might be ineffective for communication, because the vibration propagates not only to the point of contact but also across the entire surface of the nail, potentially interfering with other actuators. To create clear and focused vibration signals, previous studies have used a linear resonant actuator (LRA) to direct the vibration through a tip mounting on the bottom of the LRA [8]. However, conventional LRA modules are too large for deployment of a dense actuator array on the small surface of a typical fingernail.

Revisiting the ERM actuators, we found an unconventional solution to this challenge — *erecting* the ERM motor so that it was mounted on its rim. To illustrate, the rotating mass inside a flat-mounted ERM actuator creates a horizontal normal force along the mounted surface. Erecting an ERM actuator, therefore, can direct the normal force to the mounted surface. Furthermore, the disc actuator also touches a smaller area of the surface, and creates clear and focused signals when the motor vibrates.

Experiment and Results

Measurements were conducted to examine the concept. Six FSR402 pressure sensors were used for the measurements. We glued a rim-attached ERM actuator on the centers of three of these sensors; we fixed a flat-mounted ERM actuator on the center of the other three. In a single cycle, each vibrator was set to vibrate for 0.4 seconds, and then idle for 0.4 seconds. The analog readings of each pressure sensor were collected for 1 minute.

Results show that the rim-attached ERM actuators had significantly higher signal/noise ratios than the flat-mounted ones (Figure 2). Moreover, the disc-like ERM actuators also occupy smaller areas on the nail when mounted by their edges, making higher-resolution tactor arrays feasible to build.

Implementing High-Resolution Tactor Arrays

Two nail-mounted tactor arrays, a 5×1 array and a 1×5 array (Figure 3), were firstly implemented for evaluation. ERM actuators were mounted on artificial nails in line with the normal vector of the nail surface. To reduce the resonation effects, we fixed each ERM actuator independently by using cyanoacrylate glue. These prototype devices that we used for the evaluation not only provided an effective means for rendering clear vibrotactile signals, but they are also easily replicable for future studies.

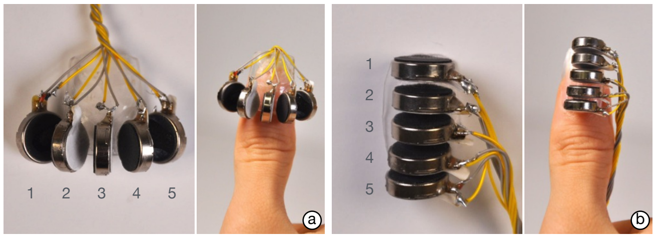


Figure 3. One-dimensional nail-mounted tactor arrays. (a) 5×1 tactor array (b) 1×5 tactor array.

Similar to wearing artificial nails, mounting the tactor array on a fingernail is a one-time effort. A user firstly aligns and sticks the tactor array, which is mounted on the artificial nail, on the fingernail with glue, then presses it down and holds it for a few seconds until the glue sets, and then trim the unwanted part of the plastic piece to make it comfortably worn. A carefully applied device will minimize the signal loss between the tactor array and the participants nail. As a result, the presented signals can be effectively perceived by skin receptors beneath the fingernail.

USER STUDIES

With the aforementioned hardware, the research investigated the delivery of rich signals to users for valid signal perception. To investigate user performance, three user studies were conducted.

Pilot Study

Before the formal study, the vibration durations and gaps of the presented signals were determined by conducting a pilot study. Six-participant (2 males, 4 females) aged 19–24 (mean age, 21.33; SD, 1.862) were recruited. Three durations (200, 400, and 600 ms) and three gaps (0, 200, and 400 ms) with sample signals were presented to the participants, who wore the two 1D tactor arrays (Figure 3) on the thumb of the nondominant hand sequentially in a counterbalanced order. During the experiment, the devices were carefully fixed on each participants thumbnail by using strong (but removable) 3M double-side tape. The devices were checked frequently during the experiment to ensure the validity of the results. The average duration of the mounting processes was approximately 3 minutes. Before the formal testing session, each participant underwent a 5-minute perception training session for familiarization with the tactile patterns.

Results show participants were generally capable of recognizing the signals when the duration was set to 400 ms, and they were able to distinguish different vibrations when the gap was set to 200 ms. These results showed that, for the ERM actuators, using a 400-ms duration and 200-ms gap achieved suffi-

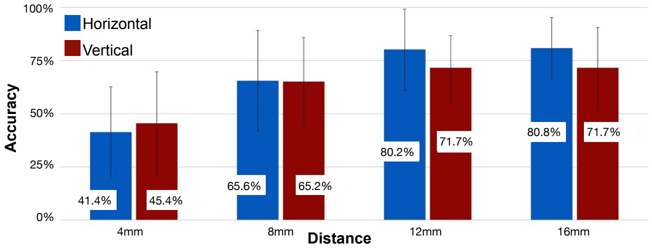


Figure 4. Experimental results on the recognition accuracy of relative direction cues

cient balance between signal perception validity and transfer efficiency; this concurs with the findings of Saket *et al.* [14].

Study 1: Absolute and Relative Spatial Cues in 2D

The first user study was conducted to understand the information transfer efficiency of the implemented 1D tactor array.

Apparatus and Participants

Twenty-four participants were recruited for testing, for which they were evenly divided into two groups. Group 1 consisted of 12 participants (10 males, 2 females) aged 19−23 years (mean age, 21.00; SD, 1.7) wearing the nail-mounted 5×1 tactor array (Figure 3a). Group 2 consisted of 12 participants (11 males) aged 19−26 years (mean age, 21.58; SD, 2.15) wearing the nail-mounted 1×5 tactor array (Figure 3b). Similar to the pilot study, all participants wore the devices on the thumb of the nondominant hand, and received a 5-minute perception training session before the formal study.

Procedures

Each trial consisted of two vibration signals. Each signal was generated by only one of five vibrators. Participants were requested to first answer whether the two signals came from the same or different vibrators. Subsequently, they were requested to identify the positions of the vibrating motor(s) according to the order of vibration. Each participant answered the questions by using his or her dominant hand to click corresponding on-screen buttons by using a mouse. The answers of every trial were recorded. Twenty-five different signals, including all two-position combinations of five vibration positions, were presented to the participants in a random order. The vibration duration was set to 400 ms, and the idle duration between two vibrations was set to 200 ms. Each signal was repeated three times to ensure the validity of signal perception. In total, 25 (signals)×10 (trials) = 250 trials were successfully performed with each participant.

Results and Discussions

1. *Delivering directional cues is possible but not very reliable* (Figure 4). When the distance between the starting and the ending vibration points was greater than or equal to 12 mm, the participants could recognize the directions of the horizontal cues from the starting point to the end point with a recognition rate of more than 80% accuracy. This suggests that horizontal direction cues, such as turn left or turn right, might be deliverable for pedestrian navigation with 1D tactor array, but the performance may be insufficient for serious uses such as route guidance in high-speed driving.

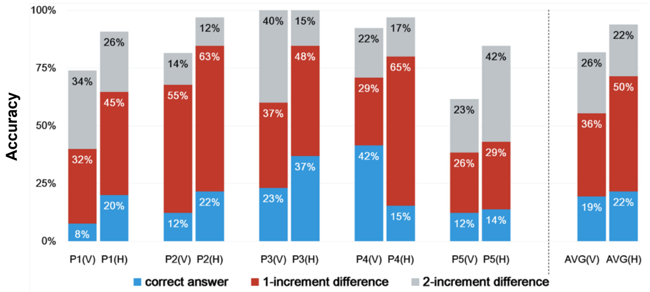
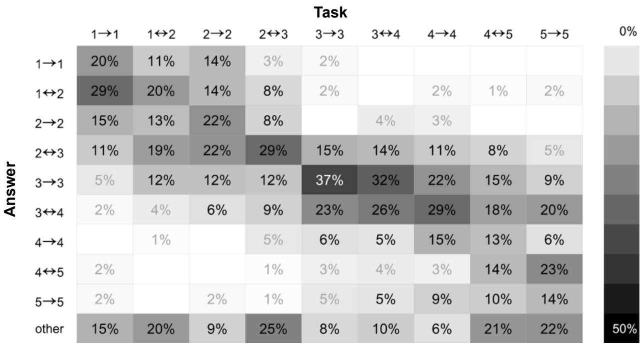


Figure 5. Experimental results on the recognition accuracy of absolute vertical (V) and horizontal (H) position cues, including 0-, 1-, and 2-increment differences.



	1→1	1↔2	2→2	2↔3	3→3	3↔4	4→4	4↔5	5→5
1→1	20%	11%	14%	3%	2%				
1↔2	29%	20%	14%	8%	2%		2%	1%	2%
2→2	15%	13%	22%	8%		4%	3%		
2↔3	11%	19%	22%	29%	15%	14%	11%	8%	5%
3→3	5%	12%	12%	12%	37%	32%	22%	15%	9%
3↔4	2%	4%	6%	9%	23%	26%	29%	18%	20%
4→4		1%		5%	6%	5%	15%	13%	6%
4↔5	2%			1%	3%	4%	3%	14%	23%
5→5	2%		2%	1%	5%	5%	9%	10%	14%
other	15%	20%	9%	25%	8%	10%	6%	21%	22%

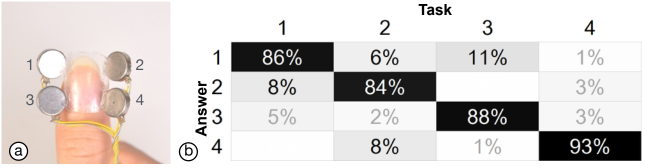
Figure 6. Presented patterns and the answers of the 5×1 tactor array.

2. *Delivering absolute positional cues is possible* (Figure 5). Although the participants could not resolve the exact position of a vibration, they mostly responded with the neighboring position; the confusion matrix is shown in Figure 6. For the horizontal positions on the 5×1 tactor array, the overall recognition accuracy reached 71.4% when the participants considered all the answers within 1-increment (±4 mm) differences; the accuracy reached 93.8% when they considered all the answers within 2-increment (±8 mm) differences. For the vertical positions on the 1×5 tactor array, the recognition accuracy reached 81.8% when the participants considered all the answers within 2-increment (±8 mm) differences. These results demonstrate the feasibility of building a 2D tactor array for dilivering more complex spatial, symbolic information, and support our further explorations.

Study 2: Absolute Spatial Cues in 2D

Apparatus and Participants

Based on the results of Study 1, a 2×2 tactor array was implemented (Figure 1). Each rim-attached vibrator was at a distance of at least 12 mm from all other vibrators to ensure reliable information transfers. Another user study was conducted to understand the information transfer efficiency of the implemented 2×2 tactor array. Twenty-four participants (19 males, 5 females) aged 19−23 years (mean age, 20.63; SD, 1.468) were recruited; they wore the 2×2 tactor array on the thumb of the nondominant hand, and received a 5-minute perception training session before the formal study.



		Task		
Answer	1	2	3	4
1	86%	6%	11%	1%
2	8%	84%		3%
3	5%	2%	88%	3%
4		8%	1%	93%

Figure 7. (a) Apparatus of Experiment 2. (b) Confusion matrix of the experimental results.

Procedures

Each trial consisted of one vibration signal. Each signal was generated by only one of the four vibrators. Participants answered the questions using their dominant hand by using a mouse to select the corresponding on-screen buttons. The answers of every trial were recorded. Four different signals were presented to the participant in a random order. Each signal was repeated three times to ensure the validity of signal perception. In total, 4 (signals)×20 (trials)×24 (participants) = 1920 trials were successfully conducted.

Results and Discussions

Figure 7 shows that the participants could recognize the positions of the vibration points with an overall accuracy of 87.8%. The results indicate the feasibility of designing further applications beyond simple notifications, such as communicating spatial, symbolic, and semantic information by using the 2×2 tactor array.

Study 3: EdgeWrite Number Delivery in 2D

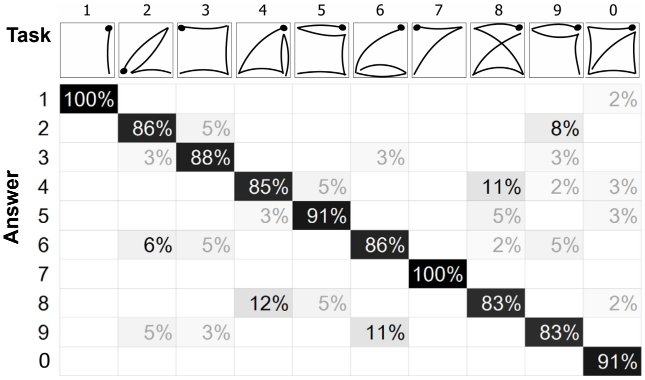
EdgeWrite [19] is a minimalist unistroke text and number symbol system for alphanumeric communication that can be delivered using a 2×2 tactor array. This study investigated the efficiency of transferring EdgeWrite numerical characters to users.

Apparatus and Participants

Ten numerical symbols were implemented on the tactor array, as shown in Figure 1. Twenty participants (9 males, 11 females) aged 18−24 years (mean = 20.25; SD = 1.71) wore the 2×2 tactor array as in Study 2, and received a 5-minute perception training session before the formal study.

Procedures

Each trial involved one of the ten EdgeWrite numerical symbols, which was delivered using the four vibrators on the participants 2×2 tactor array. Participants answered the questions by using their dominant hand to click on the corresponding on-screen buttons by using a mouse. The answers of every trial were recorded. The 10 symbols were presented to the participants in a random order. Because the goal of this study was to test the efficiency of the tactile display rather than the learnability of the EdgeWrite pattern, each participant went through a 5-minute practice session, and the EdgeWrite patterns were visible for them during the entire testing. In contrast to the previous study, each vibration duration was set to 1 second with no repeat. Because there was only one vibrator vibrating at a time, the vibrators on the tactor array neither cross-talked nor created phantom sensations [1]. In total, 10 (symbols) × 5 (trials) × 20 (participants) = 1000 trials were successfully performed. A short interview was also conducted after the testing.



	1	2	3	4	5	6	7	8	9	0
Task										
Answer										
1	100%									2%
2		86%	5%						8%	
3		3%	88%			3%			3%	
4				85%	5%			11%	2%	3%
5				3%	91%			5%		3%
6		6%	5%			86%		2%	5%	
7							100%			
8				12%	5%			83%		2%
9		5%	3%			11%			83%	
0										91%

Figure 8. Confusion matrix of the experimental results of Study 3.

Results and Discussions

Figure 8 shows that participants were able to recognize the EdgeWrite numbers with an overall accuracy of 89%. The confusion matrix shows that Numbers 1 and 7 had 100% accuracy, because each had a unique number of vibration counts: Number 1 had two vibrations and Number 7 had three vibrations. Although Number 0 (with six vibrations) also had a unique vibration count, the participants sometimes failed to recognize it. Other signals either had four vibrations (Numbers 2, 3, 6, and 9) or five vibrations (Numbers 4, 5, and 8), and the symbols were mostly misinterpreted as others that had the same vibration counts. However, the overall accuracy of each stroke was still above 82%. The results suggest that the 2×2 tactor array transferred the numerical characters with substantial reliability.

User Feedback

User feedback was gathered through a postexperimental interview. Most participants felt the relative positions of vibration points on the nail, which provided spatial cues for them to recognize the numerical characters. Three participants reported that, after becoming familiar with the patterns, they developed advanced strategies such as using the starting point position, the end point position, and the vibration counts to determine the characters. One participant felt the pair of Numbers 5 and 8 and pair of Numbers 2 and 9 were confusing, describing that he would have preferred to have used other, easier patterns instead. Two participants reported that the frequent vibration signals desensitized their skin. Two participants reported that sometimes they missed the signals because they did not know when to start, therefore they would have preferred to have received preamble signals as reminders.

DISCUSSIONS

Applications and Contributions

The proposed devices and techniques enhanced the applications of wearable interactions in two major areas: *eyes-free output* and *nail-mounted displays*. Regarding eyes-free

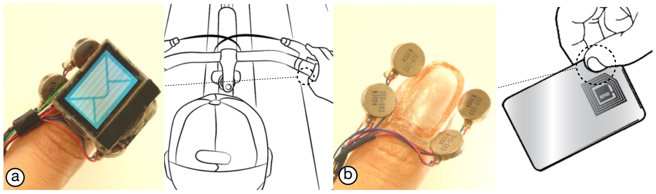


Figure 9. (a) Using a tactor array to enhance a nail-mounted display for eyes-free communication when a user is visually occupied. (b) Incorporate a nail-mounted tactor array with a radio-frequency identification (RFID) reader to perceive information from tagged everyday objects.

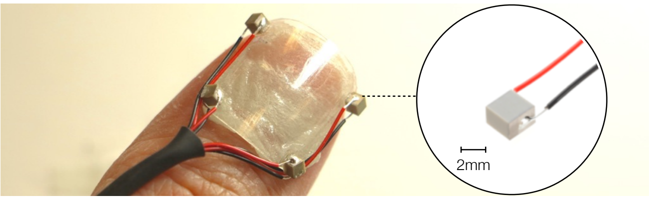


Figure 10. Miniaturized nail-mounted tactor array built with tiny piezoelectric actuators.

output, previous publications have proposed enabling eyes-free two-way communications between users and smart devices [12] or guiding the touch interactions of users with visual impairments or blindness [18]. Wearing a tactor array has potential applications to general smart objects that do not provide gesture or tactile output mechanisms. Regarding nail-mounted displays, previous studies have also proposed enabling perception with screenless touch devices [16], because researchers have concluded that, of all the channels that have been evaluated, vibration was the most reliable and fastest channel through which wearable rings can convey notifications, and that such notifications were unaffected by the users level of physical activity [13]. Using a tactor array further remove the need for visual engagement, therefore, it is suitable for applications in visually occupied scenarios such as driving, as shown in Figure 9a.

Alternative Designs and Future Work

The form of tactor array can be further miniaturized using tiny piezoelectric actuators (e.g., $2\times2\times2$ mm^3 PI PL022.30 PICMA Chip Actuators[1]), as shown in Figure 10, to meet the criteria of beauty technology [17]. The short response time (<2 ms, where ERMs and LRAs run in $30-60$ ms) of the piezo actuators further enables new opportunities for providing clearer and richer haptic signals to enhance the effectiveness and expressivity of tactile output. A nail-mounted radio-frequency identification (RFID) reader could allow users to perceive additional information during interactions with RFID-tagged everyday objects such as knowing the balance of a payment card when holding it (Figure 9b). Incorporating touch-enabling technologies, such as Touch&Activate [10] and Touché [15], into everyday objects may enable communications with objects touched by the fingers. Furthermore, directly enable touch inputs on the fingertips [3] or fingernails [7] can transform fingertips into self-contained devices for supporting user interactions.

Another possible direction for extending the application scope of the nail-mounted tactor array is using EdgeWrite patterns to deliver a relatively large set of patterns (e.g., text and arithmetic symbols) or to display a sequence of symbols (e.g., multi-digit numbers). Wearing tactors that are placed on multiple fingers [4] may also increase the vocabularies and clarity of signal presentation. To this end, researchers should also consider providing aids for users short-term sensory and working memories, such as finding robust delimiters and providing visual and auditory cues, to mitigate the degradation of the recognition performance.

CONCLUSION

In this paper, we present a system of nail-mounted tactor arrays that displays spatial cues and character information to users in an eyes-free manner. Results of a series of perceptual studies not only confirmed that mounting these tactor arrays on fingernails as tactile displays is feasible and effective, but also identified the optimal placement of ERM actuators for maximizing information transfer. The implementation of the EdgeWrite algorithm enabled the system to convey easily discriminable alphanumeric data, thus enhancing the applications of wearable interactions in eyes-free output and extending the utility of nail-mounted displays.

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