Leveraging Body Interactions to Support Immersive Analytics

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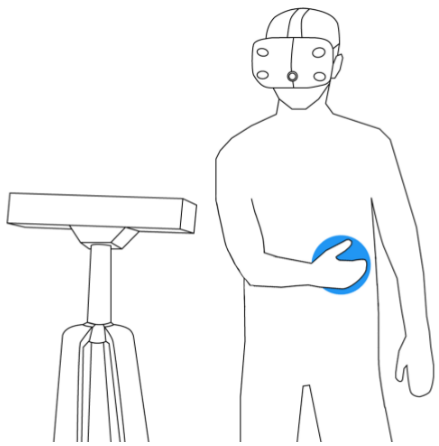

Figure 1: On body interaction for selecting a menu in a virtual reality context [22]

ABSTRACT

New immersive devices (e.g., virtual or augmented reality) enable displaying large amounts of data in space to better support data analysis. Manipulating this data efficiently is crucial, but challenging because the user must be able to activate various commands or adjust various values while remaining free to move. Using the whole body offers several valuable advantages: 1) The body provides a physical support as an interactive surface, which improves accuracy and makes it less tiring to interact; 2) Using the body does not impair mobility and avoids handling devices; 3) Proprioception makes it possible to interact eyes-free, including for choosing values in a range; 4) By leveraging spatial memory, the body helps memorizing commands, thus interacting in expert mode (i.e., perform quick actions without visual feedback). In this position paper, we analyze various ways of interacting with the body and discuss their advantages and challenges for immersive analytics.

CCS CONCEPTS

• **Human-centered computing** → **Gestural input**.

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KEYWORDS

On-body interaction; Gestural interaction; Memorization; Command selection; Data manipulation

INTRODUCTION

High-resolution wall displays, Virtual Reality, and Augmented Reality provide new possibilities for displaying data and interacting with it. They enable data spatialization for immersing users in 3D environments in which they can navigate and manipulate large amounts of data [13, 20]. However, manipulating data involves selecting commands, filtering, navigating, adjusting values, etc. Yet, these operations remain somewhat challenging because they should not impair the mobility and the interaction comfort of the user.

Common interaction devices like mice or keyboards do not support user's mobility and are not well suited for interacting in a 3D space. Specific devices (e.g., VR controllers) require handling them and offer limited capabilities for selecting commands other than by performing 3D gestures. However, 3D gestures tend to be tiring, especially when interacting with menu systems. While navigating in menu hierarchies is common and easy on the desktop, this requires more attention and more effort because gestures are performed "in the air" rather than on an easily accessible surface [1, 30, 34]. Moreover, such environments generally do not provide shortcut mechanisms such as hotkeys, due to the lack of a keyboard.

Gestural interaction offers a compelling alternative as it enables selecting multiple commands by performing movements that can be limited in size and do not require much accuracy (e.g., Marking menus [37]). When users learn gestures, they can perform them quickly and without visual feedback (i.e., expert mode). However they still generally require performing movements in the air.

In contrast, an advantage of using the whole body to interact is that it provides a surface, which should reduce fatigue and improve accuracy. Moreover, the body is by essence "mobile" and always accessible to the user, who can then keep her hands free instead of having to hold a device. Another advantage is that proprioception skills enable a user to touch accurately his body parts without looking at them. This property is particularly relevant in virtual environments where the user wears an opaque headset. Finally, the body can help to memorize gestures and their associations with commands, which allows the user to interact in expert mode rather than by selecting frequent commands in menus or tool palettes. In particular, natural landmarks help for mapping commands on these areas [7]. Because the user knows where these locations are on her body, she has no difficulty finding them back. Moreover, this kind of mapping leverages spatial memory [53], which provides a powerful means to remember command-gesture associations [22, 39, 49].

In this position paper, we consider different ways of interacting with the whole body and discuss the advantages and challenges of such an approach in the context of immersive analytics.

RELATED WORK

Common interactive devices, such as mice or keyboards, cannot be the primary means of interaction in multi-surface environments (e.g., walls plus tabletops) and/or virtual and augmented reality (HMDs, CAVEs), either because the users need to move in the environment or because the devices are not visible. Thus, a large variety of interactive techniques have been designed for such environments.

Researchers investigated the use of multi-touch, mid-air gestures, proxemics, mobile devices (e.g., tablets, smartwatch), specific controllers or other tangible objects, speech, eyes gazes, and other non-traditional interaction techniques in such environments. Most of these techniques showed promising results but are designed mostly for commands like menu selection, object manipulation or workspace navigation. These commands are necessary, but they are not enough for visual analytic tasks which need commands to perform complex selections of data points, to filter and sort data, create visualizations, etc.

Few works focused on interaction techniques for visual analytic tasks in immersive environments. Yu et al. developed multi-touch techniques to perform complex selection in 3D points clouds in large displays [71], and Coffey et al., using the same input, developed techniques to position multiple cutting planes in 3D datasets [15]. Similarly, in VR, Cordeil et al. presented ImAxes [17], interactive axes that can be directly manipulated by the user to create visualizations. The use of multi-touch and direct manipulation increases immersion, but restrict the user from interacting at a distance with an overview of the workspace. A solution to interact from a distance is to use tangible artifacts. Cordeil et al. proposed using specific controllers like physical sliders to perform data selection in VR/AR [16]. To interact on a large display, Chapuis et al. [14], Besancon et al. [9], and Langner et al. [38] used handheld multi-touch devices like smartphones or tablets tracked in space. While efficient, it necessitates for the user to carry a device with them which can be tiring if done for a long time. To avoid this problem, Horak et al. [31] used smartwatches, and von Zadow et al. [64] touch-sensitive sleeve displays for interacting with wall displays. Other studies also explored proxemics as an alternative solution to control lenses [36] or visualizations [3], but it could be restrictive for users as each of their movement can lead to a command.

Recently the improvement of tracking technologies and the development of methods to use skin as an input surface and of touch sensitive wearable led to the design of new interaction techniques using the body as an interactive surface: on-body interaction. Saidi et al. successfully used on-body interaction concurrently with a 3D mouse for data manipulation in immersive environments [52]. The use of direct interaction with body parts for interacting in immersive environments has been explored by Serrano et al. for a navigation task [55]. However, to our knowledge, the use of direct on-body interactions for visual analytics has not been studied yet. This paper steps in that direction.

INTERACTING WITH THE BODY

Interacting with the whole body offers a promising way of interacting with environments that promote user mobility like large displays and virtual or augmented reality. It provides ways to interact at different scales (e.g., micro-gestures, mid-air gestures, body postures) depending on the context of interaction. In this section, we briefly describe the methods used so far for detecting whole body and on-body interactions, and discuss various interaction designs.

Input and Output on the Skin

Figure 2: Skin-worn sensing devices [47]

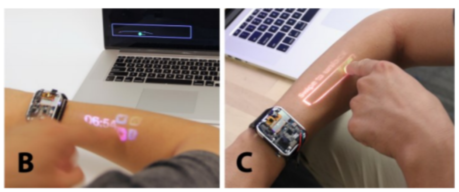

Figure 3: Depth-sensing detection for interacting on the skin using a smartwatch [69]

Various technologies were presented to detect user interaction on the skin so far [58]. Innovative methods such as using image recognition [57], sound waves [29, 72], depth sensors [28, 69], or skin-worn conductive surfaces [47, 66] were produced for interacting mostly in mobile contexts. Indeed, such devices are either worn by the user (Figure 2-3) or external and located in its surroundings [27, 28] for avoiding to impair user mobility.

Another way of recognizing user gestures on the body is to use hand-worn devices like the Roly-Poly mouse [48, 52] or controllers [22] such as those provided by the HTC Vive [60] or the Oculus Rift [21] for example. Interestingly, the Roly-Poly mouse detects hand tilts and rotations which provides more expressivity to the users when sliding on their forearm to control precisely continuous variables.

Output on the skin can involve different senses (e.g., vision or touch). Visual output is usually performed using projectors to display graphical elements on the skin [27–29, 69] which is convenient to guide users and provide signifiers for interacting. At the same time, multi-touch can be leveraged to provide feedforward or feedback using electro-tactile devices [68] or temperature inducing devices [67]. The latter approaches do not rely on vision, thus enable eyes-free stimuli that might be less disrupting for users when they have to focus on their primary task.

Sensing technologies have evolved drastically in recent years to reach the point where they are lightweight and can be worn by the user. The current challenges for skin-worn devices concern mostly their thickness and rigidity to avoid hindering tactile sensations and match perfectly body curves.

Designing Body Interactions

Interacting with the body provides various input modalities such as skin input, mid-air gestures, and body postures that enrich interaction expressivity. This rich set of possibilities that body interaction enables has yet to be explored in more depth by interaction designers. Below we present several examples of body interaction designs that support user mobility and data manipulation.

Remote pointing and mid-air gestures. There is a considerable amount of work on pointing (object selection) in immersive environments (see [2, 45] for overviews). The most common technique is ray-casting, the user shows with her hand (or head, eyes, or a device) the area to select. Ray-casting lacks of precision and should be complemented or replaced by other techniques when precision is needed. Mid-air gestures (in 3D) is also a common modality to interact in immersive environments (see [23] for a survey). However, there are no standard gestures set, and mid-air gestures are tiring [30, 34, 46]. Thus mid-air gestures should be designed to reduce fatigue (e.g., relaxed position of the arms), as Liu et al. proposed with Gunslinger [42], and learning should be taken into account.

Pointing at body parts. Several studies focused on pointing at different parts of the body to select commands [22, 56, 65] (Figure 4). This simple approach allows the user to easily select numerous commands, and even to control continuous values by leveraging on the sense of distance from body landmarks [56]. Moreover, interaction designers can easily design hierarchies of commands to access many commands [22] for quickly selecting or filtering data.

Figure 4: Pointing at body parts for command selection [56]

Continuous interaction. Controlling continuous variables is an important task for filtering data. The forearm, in this case, provides natural extremities (i.e., the elbow and the wrist) and a physical surface for supporting continuous interactions [52]. By using a device that senses hand inclination [6, 48], the user can then perform expressive gestures with precise movements. With this approach, the user can even take advantage of the curvature of the forearm to control several variables simultaneously.

Visuospatial landmarks. The human body features visuospatial landmarks such as flexure lines or knuckles that can be leveraged to guide the user when interacting. They enable, for example, invisible interfaces [25, 26] that are interesting to perform quick interactions to control a remote device eyes-free [19]. Moreover, proprioception helps to create a frame of reference for interacting with invisible elements in the air [24] or on a tabletop [59]. This capability builds on human spatial skills that involve immediate memory [43]. In the context of immersive analytics, it can help to place specific actions on these landmarks (e.g., specific filtering functions) to remember them like bookmarks.

Figure 5: Natural visual landmarks help users memorize [7]

Semantic aids. Body landmarks have been shown to help memorizing commands when pointing on the forearm [7] (Figure 5). They can also serve to leverage semantic memory, by associating body landmarks with commands and stories that relate to them. This idea takes inspiration from the method of Loci [70], an ancient memorization technique that is very efficient [11, 18]. This principle has been adapted as a remote pointing technique [49] and on-body technique [22]. While the first of these studies showed the efficiency of this approach, the second study demonstrated that creating stories related to the commands to memorize can significantly increase their recall. Moreover, the body and its landmarks (e.g., a scar) evoke personal stories, which makes it well suited for using this type of techniques.

Engaging interactions. Not only the forearms but other parts of the body such as the feet provide interesting interaction capabilities [62]. They can be used for interacting with sensing floors [54] and bottom areas on large displays [35]. More generally, body postures is an interesting way for interacting [5] as it supposedly promotes user engagement in their activities [44]. Based on the user body posture, some automatic actions could be performed to support this effort, e.g., (i) when the user sits, the system could adapt the visualization from a room scale to a desk scale, and (ii) using user postures, the system could detect when several users collaborate and adapt its visualization.

Micro-interactions. The human hand dexterity enables micro-interactions by moving the thumb on the other fingers of the same hand [32]. With proper recognition, many gestures can be recognized efficiently [57], which provides a powerful way of interacting using only one hand and finger. By using two hands in parallel, the user can thus select many commands for sorting and navigating data while keeping them free for interacting with physical objects. This last example demonstrates that, by leveraging the human body, on-body interaction enables situated interactions that require minimal input channels.

Multi-user interaction. Co-located collaboration is an important aspect of immersive analytics [10]. However, interaction techniques designed especially for multi-user in immersive environments are rare [33, 41, 50]. Liu [40] suggests that *pointing on users* can be used to exchange data or delegate tasks. Directly touching the body of a collaborator to enable collaborative interaction is not reasonable for social reasons [61]. However pointing remotely at different body parts of a collaborator while performing a given body posture (e.g., straightening the arm) might provide opportunities for designing rich vocabularies for multi-user interaction.

CHALLENGES

Using body interactions in the context of immersive analytics raises several challenges. First, this type of interaction is new for most users, and they have been trained to interact in a different manner (i.e., with PCs and mobile devices) for a long time. This can be a hindrance for learning new techniques. Moreover, users are not accustomed to performing movements that involve several body parts, which may require some small initial training. Moreover, as stated by the "Paradox of the active user" [12], users tend to favor short-term solutions even if they know that more efficient methods exist. However, these environments are new and require more efficient interaction capabilities that those generally provided, which might help emerge alternate ways of interacting.

Number of Commands. Manipulating large quantities of data of different sorts may require using a large number of commands. While some gestural interaction techniques provide large sets of gestures [4, 37, 73], they tend not to provide convenient hierarchical structures, which facilitate user learning. As said above, the natural landmarks provided by the body should help to guide users to navigate these hierarchies as they provide semantic aids to facilitate recall. However, few studies focus on the memorization of gestures in a situated context, and more research is needed to study these possibilities and evaluate their efficiency.

Gesture learning. Teaching users how to perform gestures is another challenging aspect of on-body interaction. In a recent paper, Bergstrom-Lehtovirta et al. [8] investigated users' understanding of remote visual stimuli for interacting on the skin. They showed that the curvature of the forearm affects user decisions when pointing according to a 2D stimulus. Hence, as said above, pointing on the body may involve some difficulties for inexperienced users. Another study by Vo et al. [63] also showed issues related to external stimuli when learning on-body interactions. Users had to perform directional mark on their belly, but sometimes confused the direction with its opposite because they interpreted the stimuli as a mirror or vice-versa.

Fatigue-induced Movements. Using the whole body as an interaction surface can be quite tiring. Micro-gestures provide a compelling alternative as they only require small movements. Still, even small movements of the fingers can be tiring after a long time, especially movements that involve high tension on the body joints [51]. A thorough analysis is thus needed in future research to assess which body parts should preferably be used, and how they should be used, for long-term usage.

Sensing Requirements. The sensing capabilities of skin-worn devices for detecting gestures on the skin significantly improved in recent years. This approach, however, does not enable mid-air gesture or hand posture recognition. Techniques based on vision can alleviate these limitations but they require to carry a camera on the body [57], or an environment augmented with tracking devices [56, 65]. Overall, precisely detecting touch or mid-air gestures in these contexts remains challenging because this requires using expensive or somewhat cumbersome devices.

CONCLUSION

As we showed in this position paper, using the body for interacting in the context of immersive analytics is promising for many reasons. However, recognizing body interactions is still challenging and exploring various ways to teach these interactions to users raises interesting questions that need further investigations in future work. We believe that new interactive contexts such as immersive analytics cannot be manipulated using old desktop metaphors, but should be addressed with a novel look on how users can manipulate data using their whole body.

REFERENCES

[1] S. Al-Megren, A. Kharrufa, J. Hook, A. Holden, S. Sutton, & P. Olivier. 2015. Comparing fatigue when using large horizontal and vertical multi-touch interaction displays. *INTERACT '15*. Springer, 156–164. **10.1007/978-3-319-22723-8_13**

[2] F. Argelaguet & C. Andujar. 2013. A survey of 3D object selection techniques for virtual environments. *Computers & Graphics* 37, 3, 121 – 136. **10.1016/j.cag.2012.12.003**

[3] S. K. Badam, F. Amini, N. Elmqvist, & P. Irani. 2016. Supporting visual exploration for multiple users in large display environments. *VAST '16*. IEEE, 1–10. **10.1109/VAST.2016.7883506**

[4] G. Bailly, E. Lecolinet, & L. Nigay. 2008. Flower menus: A new type of marking menu with large menu breadth, within groups and efficient expert mode memorization. *AVI '08*. ACM, 15–22. **10.1145/1385569.1385575**

[5] T. Baudel & M. Beaudouin-Lafon. 1993. Charade: Remote control of objects using free-hand gestures. *CACM* 36, 7, 28–35. **10.1145/159544.159562**

[6] P. Baudisch, M. Sinclair, & A. Wilson. 2006. Soap: A pointing device that works in mid-air. *UIST '06*. ACM, 43–46. **10.1145/1166253.1166261**
[7] J. Bergstrom-Lehtovirta, S. Boring, & K. Hornbæk. 2017. Placing and recalling virtual items on the skin. *CHI '17*. ACM, 1497–1507. **10.1145/3025453.3026030**
[8] J. Bergstrom-Lehtovirta, K. Hornbæk, & S. Boring. 2018. It's a wrap: Mapping on-skin input to off-skin displays. *CHI '18*. ACM, Article 564, 11 pages. **10.1145/3173574.3174138**
[9] L. Besançon, M. Ammi, & T. Isenberg. 2017. Pressure-based gain factor control for mobile 3D interaction using locally-coupled devices. *CHI '17*. ACM, 1831–1842. **10.1145/3025453.3025890**
[10] M. Billinghurst, M. Cordeil, A. Bezerianos, & T. Margolis. 2018. *Collaborative Immersive Analytics*. Springer, 221–257. **10.1007/978-3-030-01388-2_8**
[11] G. G. Briggs, S. Hawkins, & H. F. Crovitz. 1970. Bizarre images in artificial memory. *Psychonomic Science* 19, 6, 353–354. **10.3758/BF03328856**
[12] J. M. Carroll & M. B. Rosson. 1987. Interfacing thought: Cognitive aspects of human-computer interaction. MIT Press, Cambridge, MA, USA, Chapter Paradox of the Active User, 80–111. **http://dl.acm.org/citation.cfm?id=28446.28451**
[13] T. Chandler, M. Cordeil, T. Czauderna, T. Dwyer, J. Glowacki, C. Goncu, M. Klapperstueck, K. Klein, K. Marriott, F. Schreiber, & E. Wilson. 2015. Immersive analytics. *BDVA '15*. IEEE, 1–8. **10.1109/BDVA.2015.7314296**
[14] O. Chapuis, A. Bezerianos, & S. Frantzeskakis. 2014. Smarties: An input system for wall display development. *CHI '14*. ACM, 2763–2772. **10.1145/2556288.2556956**
[15] D. Coffey, N. Malbraaten, T. B. Le, I. Borazjani, F. Sotiropoulos, A. G. Erdman, & D. F. Keefe. 2012. Interactive slice WIM: Navigating and interrogating volume data sets using a multisurface, multitouch VR interface. *IEEE TVCG* 18, 10, 1614–1626. **10.1109/TVCG.2011.283**
[16] M. Cordeil, B. Bach, , E. Wilson, & T. Dwyer. 2017. Design space for spatio-data coordination: Tangible interaction devices for immersive information visualisation. *PacificVis '17*. IEEE, 46–50. **10.1109/PACIFICVIS.2017.8031578**
[17] M. Cordeil, A. Cunningham, T. Dwyer, B. H. Thomas, & K. Marriott. 2017. ImAxes: Immersive axes as embodied affordances for interactive multivariate data visualisation. *UIST '17*. ACM, 71–83. **10.1145/3126594.3126613**
[18] H. F. Crovitz. 1971. The capacity of memory loci in artificial memory. *Psychonomic Science* 24, 4, 187–188. **10.3758/BF03335561**
[19] N. Dezfuli, M. Khalilbeigi, J. Huber, F. Müller, & M. Mühlhäuser. 2012. PalmRC: Imaginary palm-based remote control for eyes-free television interaction. *EuroITV '12*. ACM, 27–34. **10.1145/2325616.2325623**
[20] T. Dwyer, K. Marriott, T. Isenberg, K. Klein, N. Riche, F. Schreiber, W. Stuerzlinger, & B. H. Thomas. 2018. *Immersive Analytics: An Introduction*. Springer, Cham, 1–23. **10.1007/978-3-030-01388-2_1**
[21] Facebook. 2019. Oculus Rift. Retrieved Feb. 2019 from **https://www.oculus.com/rift/#oui-csl-rift-games=robo-recall**
[22] B. Fruchard, E. Lecolinet, & O. Chapuis. 2018. Impact of semantic aids on command memorization for on-body interaction and directional gestures. *AVI '18*. ACM, Article 14, 9 pages. **10.1145/3206505.3206524**
[23] C. Groenewald, C. Anslow, J. Islam, C. Rooney, P. Passmore, & W. Wong. 2016. Understanding 3D mid-air hand gestures with interactive surfaces and displays: A systematic literature review. *HCI '16*. BCS, Article 43, 13 pages. **10.14236/ewic/HCI2016.43**
[24] S. Gustafson, D. Bierwirth, & P. Baudisch. 2010. Imaginary interfaces: Spatial interaction with empty hands and without visual feedback. *UIST '10*. ACM, 3–12. **10.1145/1866029.1866033**
[25] S. Gustafson, C. Holz, & P. Baudisch. 2011. Imaginary phone: Learning imaginary interfaces by transferring spatial memory from a familiar device. *UIST '11*. ACM, 283–292. **10.1145/2047196.2047233**
[26] S. G. Gustafson, B. Rabe, & P. M. Baudisch. 2013. Understanding palm-based imaginary interfaces: The role of visual and tactile cues when browsing. *CHI '13*. ACM, 889–898. **10.1145/2470654.2466114**

[27] C. Harrison, H. Benko, & A. D. Wilson. 2011. Omnitouch: Wearable multitouch interaction everywhere. *UIST '11*. ACM, 441–450. **10.1145/2047196.2047255**

[28] C. Harrison, S. Ramamurthy, & S. E. Hudson. 2012. On-body interaction: Armed and dangerous. *TEI '12*. ACM, 69–76. **10.1145/2148131.2148148**

[29] C. Harrison, D. Tan, & D. Morris. 2010. Skinput: Appropriating the body as an input surface. *CHI '10*. ACM, 453–462. **10.1145/1753326.1753394**

[30] J. D. Hincapié-Ramos, X. Guo, P. Moghadasian, & P. Irani. 2014. Consumed endurance: A metric to quantify arm fatigue of mid-air interactions. *CHI '14*. ACM, 1063–1072. **10.1145/2556288.2557130**

[31] T. Horak, S. K. Badam, N. Elmqvist, & R. Dachselt. 2018. When David meets Goliath: Combining smartwatches with a large vertical display for visual data exploration. *CHI '18*. ACM, Article 19, 13 pages. **10.1145/3173574.3173593**

[32] D.-Y. Huang, L. Chan, S. Yang, F. Wang, R.-H. Liang, D.-N. Yang, Y.-P. Hung, & B.-Y. Chen. 2016. Digitspace: Designing thumb-to-fingers touch interfaces for one-handed and eyes-free interactions. *CHI '16*. ACM, 1526–1537. **10.1145/2858036.2858483**

[33] P. Isenberg & D. Fisher. 2009. Collaborative brushing and linking for co-located visual analytics of document collections. *Computer Graphics Forum* 28, 3, 1031–1038. **10.1111/j.1467-8659.2009.01444.x**

[34] S. Jang, W. Stuerzlinger, S. Ambike, & K. Ramani. 2017. Modeling cumulative arm fatigue in mid-air interaction based on perceived exertion and kinetics of arm motion. *CHI '17*. ACM, 3328–3339. **10.1145/3025453.3025523**

[35] R. Jota, P. Lopes, D. Wigdor, & J. Jorge. 2014. Let's kick it: How to stop wasting the bottom third of your large screen display. *CHI '14*. ACM, 1411–1414. **10.1145/2556288.2557316**

[36] U. Kister, P. Reipschläger, F. Matulic, & R. Dachselt. 2015. BodyLenses: Embodied magic lenses and personal territories for wall displays. *ITS '15*. ACM, 117–126. **10.1145/2817721.2817726**

[37] G. Kurtenbach & W. Buxton. 1993. The limits of expert performance using hierarchic marking menus. *INTERCHI '93*. IOS Press, 482–487. **http://dl.acm.org/citation.cfm?id=164632.164977**

[38] R. Langner, U. Kister, & R. Dachselt. 2019. Multiple coordinated views at large displays for multiple users: Empirical findings on user behavior, movements, and distances. *IEEE TVCG* 25, 608–618. Issue 1. **10.1109/TVCG.2018.2865235**

[39] F. C. Y. Li, D. Dearman, & K. N. Truong. 2009. Virtual shelves: Interactions with orientation aware devices. *UIST '09*. ACM, 125–128. **10.1145/1622176.1622200**

[40] C. Liu. 2014. Leveraging physical human actions in large interaction spaces. *UIST '14 Adjunct*. ACM, 9–12. **10.1145/2658779.2661165**

[41] C. Liu, O. Chapuis, M. Beaudouin-Lafon, & E. Lecolinet. 2017. CoReach: Cooperative gestures for data manipulation on wall-sized displays. *CHI '17*. ACM, 6730–6741. **10.1145/3025453.3025594**

[42] M. Liu, M. Nancel, & D. Vogel. 2015. Gunslinger: Subtle arms-down mid-air interaction. *UIST '15*. ACM, 63–71. **10.1145/2807442.2807489**

[43] G. A. Miller. 1956. The magical number seven, plus or minus two: some limits on our capacity for processing information. *Psychological review* 63, 2, 81. **10.1037/h0043158**

[44] F. F. Mueller, R. Byrne, J. Andres, & R. Patibanda. 2018. Experiencing the body as play. *CHI '18*. ACM, Article 210, 13 pages. **10.1145/3173574.3173784**

[45] M. Nancel, E. Pietriga, O. Chapuis, & M. Beaudouin-Lafon. 2015. Mid-air pointing on ultra-walls. *ACM ToCHI* 22, 5, 62 pages. **10.1145/2766448**

[46] M. Nancel, J. Wagner, E. Pietriga, O. Chapuis, & W. Mackay. 2011. Mid-air pan-and-zoom on wall-sized displays. *CHI '11*. ACM, 177–186. **10.1145/1978942.1978969**

[47] A. S. Nittala, A. Withana, N. Pourjafarian, & J. Steimle. 2018. Multi-touch skin: A thin and flexible multi-touch sensor for on-skin input. *CHI '18*. ACM, Article 33, 12 pages. **10.1145/3173574.3173607**

[48] G. Perelman, M. Serrano, M. Raynal, C. Picard, M. Derras, & E. Dubois. 2015. The Roly-Poly mouse: Designing a rolling input device unifying 2D and 3D interaction. *CHI '15*. ACM, 327–336. **10.1145/2702123.2702244**

[49] S. T. Perrault, E. Lecolinet, Y. P. Bourse, S. Zhao, & Y. Guiard. 2015. Physical loci: Leveraging spatial, object and semantic memory for command selection. *CHI '15*. ACM, 299–308. **10.1145/2702123.2702126**

[50] A. Prouzeau, A. Bezerianos, & O. Chapuis. 2017. Evaluating multi-user selection for exploring graph topology on wall-displays. *IEEE TVCG* 23, 8, 1936–1951. **10.1109/TVCG.2016.2592906**

[51] Y. Rekik, R.-D. Vatavu, & L. Grisoni. 2014. Understanding users' perceived difficulty of multi-touch gesture articulation. *ICMI '14*. ACM. **10.1145/2663204.2663273**

[52] H. Saidi, M. Serrano, P. Irani, C. Hurter, & E. Dubois. 2018. Utilisation du corps comme support à l'interaction à distance avec un dispositif à multiple degrés de libertés. *IHM '18*. ACM, 1–11. **10.1145/3286689.3286692**

[53] J. Scarr, A. Cockburn, & C. Gutwin. 2013. Supporting and exploiting spatial memory in user interfaces. *Found. Trends Hum.-Comput. Interact.* 6, 1, 1–84. **10.1561/1100000046**

[54] D. Schmidt, R. Ramakers, E. W. Pedersen, J. Jasper, S. Köhler, A. Pohl, H. Rantzsch, A. Rau, P. Schmidt, C. Sterz, Y. Yurchenko, & P. Baudisch. 2014. Kickables: Tangibles for feet. *CHI '14*. ACM, 3143–3152. **10.1145/2556288.2557016**

[55] M. Serrano, B. M. Ens, & P. P. Irani. 2014. Exploring the use of hand-to-face input for interacting with head-worn displays. *CHI '14*. ACM, 3181–3190. **10.1145/2556288.2556984**

[56] G. Shoemaker, T. Tsukitani, Y. Kitamura, & K. S. Booth. 2010. Body-centric interaction techniques for very large wall displays. *NordiCHI '10*. ACM, 463–472. **10.1145/1868914.1868967**

[57] M. Soliman, F. Mueller, L. Hegemann, J. S. Roo, C. Theobalt, & J. Steimle. 2018. FingerInput: Capturing expressive single-hand thumb-to-finger microgestures. *ISS '18*. ACM, 177–187. **10.1145/3279778.3279799**

[58] J. Steimle, J. Bergstrom-Lehtovirta, M. Weigel, A. S. Nittala, S. Boring, A. Olwal, & K. Hornbæk. 2017. On-skin interaction using body landmarks. *Computer* 50, 10, 19–27. **10.1109/MC.2017.3641636**

[59] M. S. Uddin, C. Gutwin, & B. Lafreniere. 2016. HandMark menus: Rapid command selection and large command sets on multi-touch displays. *CHI '16*. ACM, 5836–5848. **10.1145/2858036.2858211**

[60] Valve. 2017. HTC Vive. `Retrieved Sept. 2017 from` **`https://www.vive.com/`**

[61] J. B. Van Erp & A. Toet. 2015. Social touch in human–computer interaction. *Frontiers in digital humanities* 2, 2.

[62] E. Velloso, D. Schmidt, J. Alexander, H. Gellersen, & A. Bulling. 2015. The feet in human–computer interaction: A survey of foot-based interaction. *ACM CSUR* 48, 2, 35 pages. **10.1145/2816455**

[63] D.-B. Vo, E. Lecolinet, & Y. Guiard. 2014. Belly gestures: Body centric gestures on the abdomen. *NordiCHI '14*. ACM, 687–696. **10.1145/2639189.2639210**

[64] U. von Zadow, W. Büschel, R. Langner, & R. Dachselt. 2014. Sleed: Using a sleeve display to interact with touch-sensitive display walls. *ITS '14*. ACM, 129–138. **10.1145/2669485.2669507**

[65] J. Wagner, M. Nancel, S. G. Gustafson, S. Huot, & W. E. Mackay. 2013. Body-centric design space for multi-surface interaction. *CHI '13*. ACM, 1299–1308. **10.1145/2470654.2466170**

[66] M. Weigel, T. Lu, G. Bailly, A. Oulasvirta, C. Majidi, & J. Steimle. 2015. iSkin: Flexible, stretchable and visually customizable on-body touch sensors for mobile computing. *CHI '15*. ACM, 2991–3000. **10.1145/2702123.2702391**

[67] G. Wilson & S. A. Brewster. 2017. Multi-moji: Combining thermal, vibrotactile & visual stimuli to expand the affective range of feedback. *CHI '17*. ACM, 1743–1755. **10.1145/3025453.3025614**

[68] A. Withana, D. Groeger, & J. Steimle. 2018. Tacttoo: A thin and feel-through tattoo for on-skin tactile output. *UIST '18*. ACM, 365–378. **10.1145/3242587.3242645**

[69] R. Xiao, T. Cao, N. Guo, J. Zhuo, Y. Zhang, & C. Harrison. 2018. LumiWatch: On-arm projected graphics and touch input. *CHI '18*. ACM, Article 95, 11 pages. **10.1145/3173574.3173669**

[70] F. Yates. 1992. *The Art of Memory*. Random House UK, London.

[71] L. Yu, K. Efstathiou, P. Isenberg, & T. Isenberg. 2012. Efficient structure-aware selection techniques for 3D point cloud visualizations with 2DOF input. *IEEE TVCG* 18, 12, 2245–2254. **10.1109/TVCG.2012.217**

[72] Y. Zhang, J. Zhou, G. Laput, & C. Harrison. 2016. SkinTrack: Using the body as an electrical waveguide for continuous finger tracking on the skin. *CHI '16*. ACM, 1491–1503. **10.1145/2858036.2858082**

[73] J. Zheng, X. Bi, K. Li, Y. Li, & S. Zhai. 2018. M3 gesture menu: Design and experimental analyses of marking menus for touchscreen mobile interaction. *CHI '18*. ACM, Article 249, 14 pages. **10.1145/3173574.3173823**