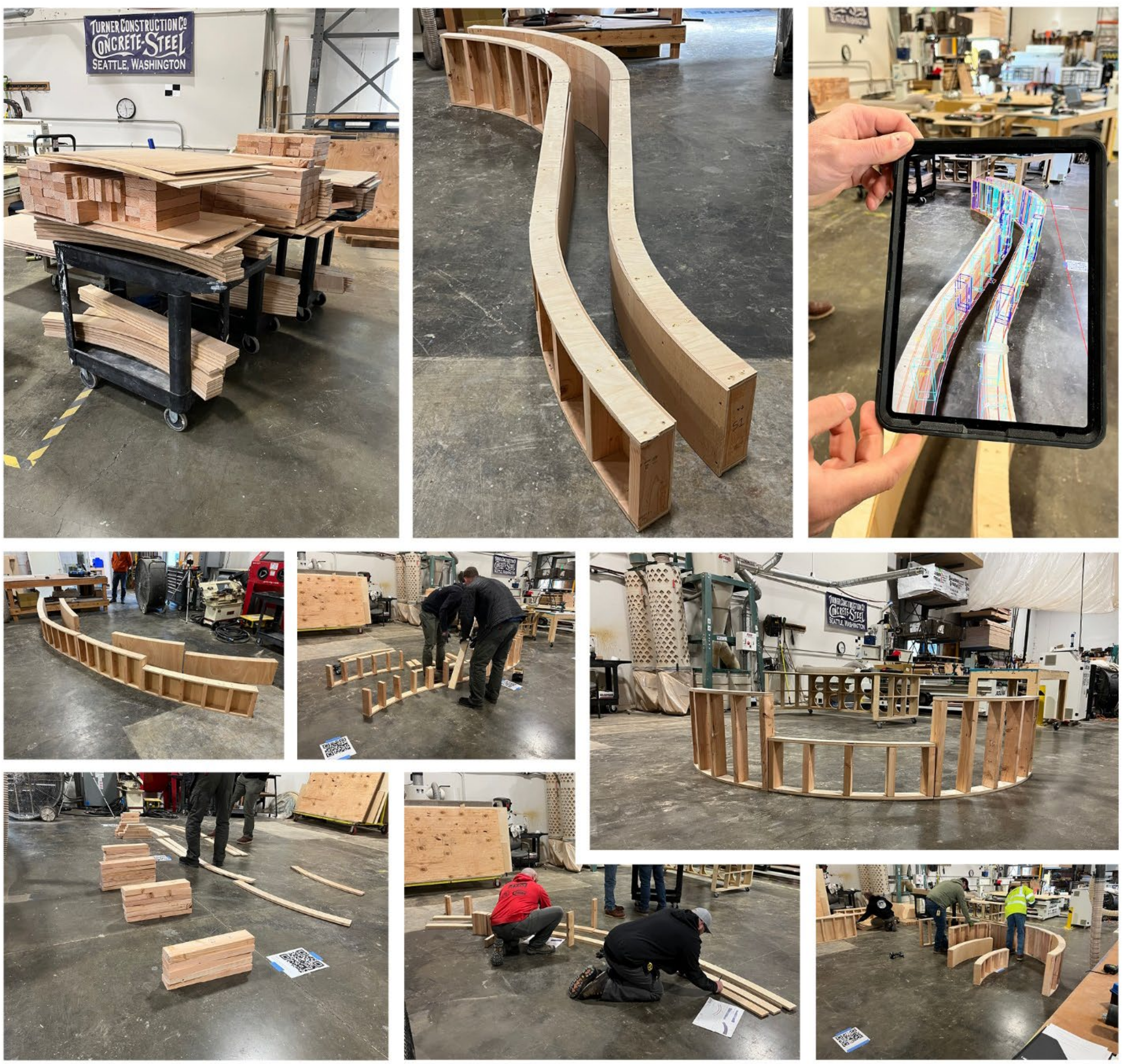
LOST IN TRANSLATION: USING TECHNOLOGY TO BRIDGE COMMUNICATION ISSUES IN CONSTRUCTION – HOW CONCRETE FORMWORK FOR UNIQUE SITUATIONS CAN LEARN FROM PREFABRICATION AND MANUFACTURING IN OTHER INDUSTRIES

Research Report | 2023-24 University of Washington College of Built Environments & Turner Construction Applied Research Consortium Project

Project Team: Morocco M Branting, Lead Researcher; Josh Lohr, Turner Advisor; Nathan Brown, Turner Advisor; Sean Beatty, Turner Advisor; Renzo di Furia, Advisor; Tyler Sprague, UW Advisor; Rob Corser, UW Advisor



COLLEGE OF BUILT ENVIRONMENTS
UNIVERSITY of WASHINGTON

Turner

EXECUTIVE SUMMARY

This research project consisted of a series of assembly studies to understand the strengths and weaknesses of using different visual communication methods when constructing digitally prefabricated concrete formwork systems. As the construction industry integrates more digital fabrication technology, the question becomes whether it is more effective to implement it on site or in a prefabrication shop. Several other industries have already reached this point of technological integration in their workflows, making their processes valuable case studies. This research centers on stationary equipment in a fabrication shop environment as a way to create a human-centric approach to digital fabrication by leveraging the knowledge base of construction workers on site. This approach capitalizes on the strengths of digital fabrication while mitigating some of its weaknesses and risks, such as the current limitations of on-site robotics and the replacement of human labor.

In the assembly trials, participants were asked to assemble wood-framed pony wall formwork using three different types of instructions: shop drawings, an assembly booklet, and a tablet with an Augmented Reality (AR) program. The assembly booklets were derived from companies such as Ikea and Lego, while the augmented reality approach was developed through in-house testing to determine the most effective way of using it. Participants expressed overwhelming enthusiasm for the proposed methods of communication and provided a wealth of feedback to refine the systems before broader testing and implementation. Both the assembly booklet and the augmented reality platform realized over 33% reductions in assembly time compared to shop drawings, which were the baseline. The alternative instruction types also outperformed the shop drawings across multiple usability ranking formats, further reinforcing the value of supplementing traditional practices with digital prefabrication and alternate communication options.

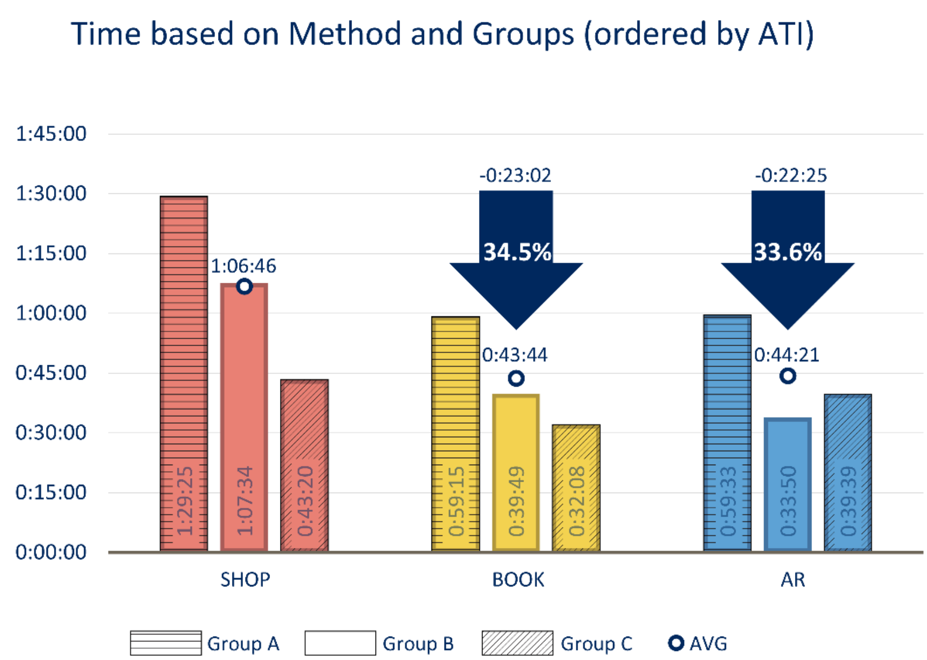
RESULTS OF ASSEMBLY STUDIES

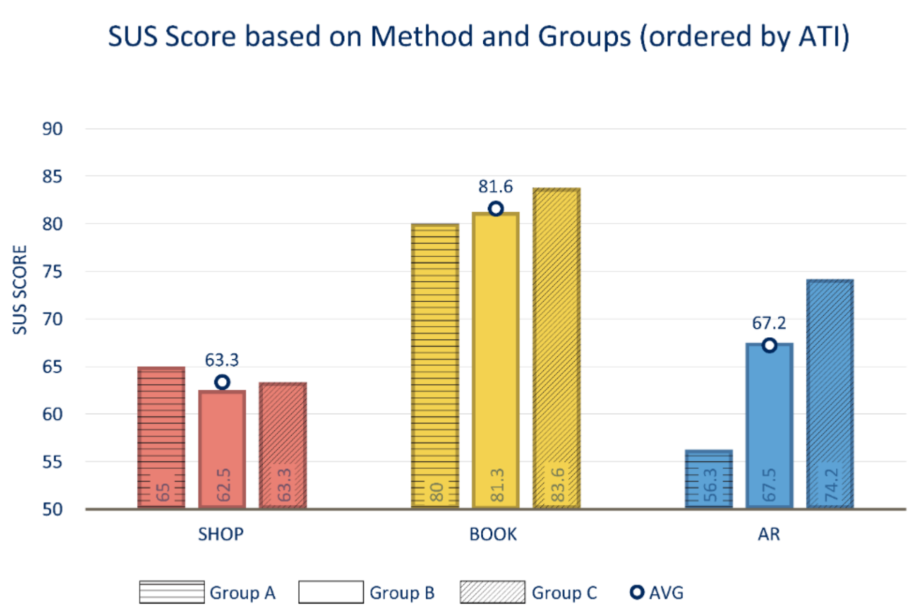
The various comments directly from the participants were the primary sources to gauge the strengths and weaknesses of each method. Surprisingly, the most successful aspect of the project was not one of the alternative instruction systems directly, but the labeling system that was developed to make them most effective. The labels consisted of fabrication and assembly information and were engraved directly on the parts utilizing a CNC router. Some participants found the system so useful that they "could have done it without drawings." The carpenters also commented that the prefabrication of the curved elements was particularly valuable to their work as it bypassed the need to manually lay out the curving radii on plywood sheets and then cut them out.

The alternative methods showed remarkable improvements in time savings during assembly and in their overall usability, as reported by participants through different surveys. The graphs on the following page illustrate the elapsed time for each instruction method by group and on average, as well as the usability scores. It is important to note that the number of participants fluctuated per group; group A had two, B had four, and C had three. Also, groups are organized by their Affinity for Technology Interaction (ATI) score, which represents their inclination to fully integrate new systems. As both alternative instruction methods show similar decreases in assembly time, the data suggests that both of these

The labeling system engraves fabrication information into the CNC'd parts, including part labels, indicators for casting face side, and information on stud locations and dimensions.

methods communicated efficiently and reduced the time required to understand the task at hand to the minimum possible, leaving only the amount of time required to actually build the formwork. The tight groupings of the System Usability Scale (SUS) scores for the shop drawings and assembly booklets indicate that these methods, which build on the tradition of using drawings to convey construction information, create a sense of familiarity and quick understanding across multiple different user groups.





TAKEAWAYS & AREAS FOR FURTHER STUDY

While this project showcases compelling results that inspire future research and implementation, the most interesting takeaway from this project is that the construction industry is more open and enthusiastic about innovation than common stereotypes may imply. Not only are companies like Turner devoting capital to research and development efforts, but the construction workers themselves are also open to doing things differently, especially when it improves their daily lives by streamlining tedious tasks. Secondly, the project provides a combination of qualitative and quantitative data that reinforces the value of VDC teams, of implementing digital fabrication workflows, and also of spending time and resources to reevaluate standard processes for ways they can be improved. It is also important to stress that the results of this study do not suggest that traditional communication methods and practices should be replaced by these alternative approaches. Each approach has its own unique set of strengths and weaknesses, meaning no one method is a one-size-fits-all solution. The path forward is one that integrates all of the investigated methods as a toolkit, where the best method for a particular task or crew is utilized rather than one that is less apt. Supplementing existing workflows also allows for more effective communication with different crews and demographics in the diverse and fluctuating industry of today without jeopardizing clear communication with individuals that have experience in the traditional approaches. Lastly, the study demonstrates the value of using participatory design processes when orchestrating changes as it provides a way for those impacted to provide feedback and collaborate in the process.

Given the success of the labeling system, future research could focus on perfecting the information engraved on parts as well as how it is represented. Repeating the assembly studies as-is but with different user groups, such as new apprentices or different trades, would create a more robust data set to analyze which would in turn create stronger takeaways or debunk them. Additionally, the scope of this project was limited to assembly only, so additional studies could focus on other stages of the prefabrication process.

METHODOLOGY

While the project culminated in the assembly trials that generated the preceding data, analysis, and takeaways, substantial work was required to ensure the assembly trials were grounded in industry research in digital prefabrication workflows. As such, this project was situated within an established prefabrication workflow and looked to optimize it by integrating digital fabrication technology. Reviewing earlier research provided critical insight into how to set up the research trials and what data to collect, as well as the best practices for different types of visual communication. The research is framed with the assumption that digital fabrication is most effective for in-factory prefabrication, which would bring the building industry closer to mass manufacturing in other industries.

Looking to Ikea and Lego as manufacturers that create kits of parts bundled with assembly instructions to achieve a predetermined design, the development of step-by-step assembly booklets became a core focus as one of the visual communication strategies to pursue. The booklets produced for the assembly trials were based on the best practices for assembly instructions uncovered during literature review, which results in a graphic style most similar to Ikea. Augmented reality was also brought into the project to gauge the impact of an emergent, high-tech approach to communicating assembly. As the study had limited time and resources for in depth testing and procurement of different AR technologies, the project utilized “Fologram,” a low-cost software option for mobile devices which provided the best balance of cost, accessibility, and performance to use as the proof of concept for AR in construction.

Quantifying the communication methods for objective comparison relied primarily on the System Usability Scale (SUS) developed by John Brooke for the Digital Equipment Corporation in 1986. The scale is backed by subsequent research and verification studies, making it a reliable method to interpret the usability of a system. The Affinity for Technology Interaction (ATI) scale was developed by Franke, Attig, and Wessel and was first published for use in 2019. It has since been verified by research and is effective in gauging the general population's inclination to use new technological systems.

Much of the theoretical basis for the execution of the project was rooted in previous R&D efforts by Turner Construction, such as the Seattle VDC department's development of automated workflows for select modeling processes. Using projects such as the Edgeform Script as a starting point, this project included developing a new script to generate fabrication-level formwork models based on input geometry. This automation was key in creating a series of different formwork walls to use in the assembly trials to reduce the potential of a participant's growing familiarity with a design to influence the data. Manually modeling fabrication geometry, which can be as detailed as modeling the accurate location of every form tie, piece of rebar, etc., is time consuming. If something needs to be changed, the rework process is even more time intensive. Automating the geometry generation with Grasshopper took an upfront time investment but allowed the team to quickly and efficiently generate subsequent formwork walls thereafter, which is important if the idea continues being developed for broader implementation in the field. Beyond the model itself, the same concepts of automation could also be applied to the generation of the shop drawings and assembly booklet making them less resource intensive to produce. ▪

BIBLIOGRAPHY

Agrawala, Maneesh, Doantam Phan, Julie Heiser, John Haymaker, Jeff Klingner, Pat Hanrahan, and Barbara Tversky. 2003. “Designing Effective Step-by-Step Assembly Instructions.” *ACM Transactions on Graphics* 22 (3): 828–37. https://doi.org/10.1145/882262.882352.

Blough, Lawrence. 2011. “Digital Tracery - Fabricating Traits.” In *Matter: Material Processes in Architectural Production*. Taylor & Francis Group.

Bork, Robert. 2023. “Paper Thin? The Evidence for 12th-Century Gothic Design Drawings.” *Arts* 12 (6): 220. https://doi.org/10.3390/arts12060220.

Brooke, John. 1995. “SUS: A Quick and Dirty Usability Scale.” *Usability Eval. Ind.* 189 (November).

Buchli, Jonas, Markus Giftthaler, Nitish Kumar, Manuel Lussi, Timothy Sandy, Kathrin Dörfler, and Norman Hack. 2018. “Digital in Situ Fabrication - Challenges and Opportunities for Robotic in Situ Fabrication in Architecture, Construction, and Beyond.” *Cement and Concrete Research*, SI : Digital concrete 2018, 112 (October):66–75. https://doi.org/10.1016/j.cemconres.2018.05.013.

Buswell, R. A., W. R. Leal de Silva, S. Z. Jones, and J. Dirrenberger. 2018. “3D Printing Using Concrete Extrusion: A Roadmap for Research.” *Cement and Concrete Research*, SI : Digital concrete 2018, 112 (October):37–49. https://doi.org/10.1016/j.cemconres.2018.05.006.

Crane, Robert, and Jeremiah Woolsey. 1992. “Isometric Drawings Enhance Assembly.” *Assembly* 35 (May). https://go-gale-com.offcampus.lib.washington.edu/ps/i.do?p=GBIB&u=wash_main&id=GALE|A12274454&v=2.1&it=r.

Deutsch, Randy. 2011. *BIM and Integrated Design: Strategies for Architectural Practice*. Newark, UNITED STATES: John Wiley & Sons, Incorporated. http://ebookcentral.proquest.com/lib/washington/detail.action?docID=697537.

Dougherty, Connor. 2018. “Piece by Piece, a Factory-Made Answer for a Housing Squeeze - The New York Times.” *New York TImes*, June 7, 2018. https://www.nytimes.com/2018/06/07/business/economy/modular-housing.html.

Dunn, Nick. 2012. *Digital Fabrication in Architecture*. London, UNITED KINGDOM: Laurence King Publishing. http://ebookcentral.proquest.com/lib/washington/detail.action?docID=1876132.

Fardhosseini, Mohammad Sadra. 2021. “A Quantitative Analysis of the Impact of Integrating Digital Technology for Formwork Fabrication on Human Factors Perspectives.” Seattle: University of Washington Libraries. https://digital.lib.washington.edu/researchworks/bitstream/handle/1773/47369/Fardhosseini_washington_0250E_22891.pdf?sequence=1&isAllowed=y.

Federal Reserve Bank St. Louis. 2021. “Private Non-Farm Business Sector: Multifavtor Productivity (Total Factor).”

Fologram, dir. 2021. *Using the HoloLens to Build the Royal Hobart Hospital*. https://www.youtube.com/watch?v=swA0pQcS-Is.

Fologram. 2024. “Model Placement.” Fologram Instruction Documents. 2024. https://docs.fologram.com/ee913f72885c43d6b727ec7d025e4d13#Model_placement.

Franke, Thomas, Christiane Attig, and Daniel Wessel. 2019. “A Personal Resource for Technology Interaction: Development and Validation of the Affinity for Technology Interaction (ATI) Scale.” *International Journal of Human–Computer Interaction* 35 (6): 456–67. https://doi.org/10.1080/10447318.2018.1456150.

Frixione, Marcello, and Antonio Lombardi. 2015. “Street Signs and Ikea Instruction Sheets: Pragmatics and Pictorial Communication.” *Review of Philosophy and Psychology* to appear (March). https://doi.org/10.1007/s13164-014-0216-1.

Funk, Johannes, and Ludger Schmidt. 2021. “Evaluation of an Augmented Reality Instruction for a Complex Assembly Task: Comparison of a Smartphone-Based Augmented Reality Instruction with a Conventional Paper Instruction for the Teach-in Phase in Manual Assembly.” *I-Com* 20 (1): 63–72. https://doi.org/10.1515/icom-2021-0005.

Gao, Zhili, Russel C. Walters, Edward Jaselskis, and Terry J Wipf. 2006. “Approaches to Improving the Quality of Construction Drawings from Owner’s Perspective,” November. https://ascelibrary.org/doi/epdf/10.1061/%28ASCE%290733-9364%282006%29132%3A11%281187%29.

Hamid, Montasser, Osama Tolba, and Ahmed El Antably. 2018. "BIM Semantics for Digital Fabrication: A Knowledge-Based Approach." *Automation in Construction* 91 (March):62–82. https://doi.org/10.1016/j.autcon.2018.02.031.

Hartanto, Hugo Adrian, Irena Krishanti Makrie, Violitta Yesmaya, and Permana Gustav Halfian. 2019. "The Development of Furniture Assembly Instruction Based on Augmented-Reality." *ComTech: Computer, Mathematics and Engineering Applications* 10 (2): 75–81. https://doi.org/10.21512/comtech.v10i2.5853.

Horton, William. 1993. "The Almost Universal Language: Graphics for International Documents." *Technical Communication* 40 (4): 682–93.

Lezhnina, Olga, and Gábor Kismihók. 2020. "A Multi-Method Psychometric Assessment of the Affinity for Technology Interaction (ATI) Scale." *Computers in Human Behavior Reports* 1 (January):100004. https://doi.org/10.1016/j.chbr.2020.100004.

Mahmood, Bilawal, SangUk Han, and Dong-Eun Lee. 2020. "BIM-Based Registration and Localization of 3D Point Clouds of Indoor Scenes Using Geometric Features for Augmented Reality." *Remote Sensing* 12 (14): 2302. https://doi.org/10.3390/rs12142302.

Modular Building Institute. 2023. "2023 Permanent Modular Construction Report." https://mbimodularbuildinginstitute.growthzoneapp.com/ap/CloudFile/Download/LwYRWRzp.

Raspall, Felix. 2015. "A Procedural Framework for Design to Fabrication." *Automation in Construction* 51 (March):132–39. https://doi.org/10.1016/j.autcon.2014.12.003.

Sadeghi-Niaraki, Abolghasem, and Soo-Mi Choi. 2020. "A Survey of Marker-Less Tracking and Registration Techniques for Health & Environmental Applications to Augmented Reality and Ubiquitous Geospatial Information Systems." *Sensors (Basel, Switzerland)* 20 (10): 2997. https://doi.org/10.3390/s20102997.

Schumacher, Peter. 2007. "Creating Effective Illustrations for Pictorial Assembly Instructions." *Information Design Journal (IDJ)* 15 (2): 97–109. https://doi.org/10.1075/idj.15.2.01sch.

Schumacher, Peter. 2013. "A Pattern Language for Pictorial Assembly Instructions (PAIs)." *Information Design Journal* 20 (December). https://doi.org/10.1075/idj.20.2.03sch.

Shi, Yao, Xiaofeng Zhang, Ran zhang, Zhou Yang, Xiao Tang, Hongni Ye, and Yi Wu. 2023. "BrickPal: Augmented Reality-Based Assembly Instructions for Brick Models." arXiv. http://arxiv.org/abs/2307.03162.

Slepicka, Martin, Simon Vilgertshofer, and André Borrmann. 2021. "Fabrication Information Modeling: Closing the Gap between Building Information Modeling and Digital Fabrication." In *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, 38:9–16. Waterloo, Canada: IAARC Publications. https://www.proquest.com/docview/2642454729/abstract/667894E9CE7C4334PQ/1.

SOM. 2023. "Angelus Novus Vault – Palazzo Mora, Venice." SOM. May 18, 2023. https://www.som.com/story/angelus-novus-vault-palazzo-mora-venice/.

Turner Construction. 2023. "Case Study: Innovation in Digital Fabrication Prefabricated Formwork." https://www.turnerconstruction.com/uploads/Case-Study-Innovation-in-Digital-Fabrication.pdf.

US Bureau of Labor Statistics. 2021. "Total Factor Productivity for Construction (NAICS23)."

US GAO, U. S. Government Accountability Office. 2022. "Science & Tech Spotlight: Extended Reality Technologies | U.S. GAO." GAO-22-105541. US GAO. https://www.gao.gov/products/gao-22-105541.

Yan, Wei. 2022. "Augmented Reality Instructions for Construction Toys Enabled by Accurate Model Registration and Realistic Object/Hand Occlusions." *Virtual Reality* 26 (2): 465–78. https://doi.org/10.1007/s10055-021-00582-7.