

Running Header: Tool Use Affects Spatial Perception

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Tools do not just expand our capabilities. They change what we can do, and in doing so, they change who we are. Serena is Serena because of what she can do with a tennis racket. Tiger is Tiger because of what he can do with a golf club. In changing what we can do, tools also change the very way we perceive the spatial layout of the world. Objects beyond arm's reach appear closer when we wield a tool that can expand out to the object. Catchable objects seem to move faster when we wield a tool that is less effective for catching the object. These examples illustrate how the basic processes of spatial vision are impacted by tool use.

Tool Use Affects Spatial Perception

Tools fundamentally change what a person can do. This expanded behavioral repertoire changes how the perceiver sees the spatial layout of the environment. Tools that expand one's abilities make targets appear closer, bigger, and slower. Tools that restrict one's abilities make targets appear farther, smaller, and faster. Tools are an extension of the body. Individuals who are blind and use a cane when they walk describe how they feel the curb, rather than the cane itself. Tennis players think of the racket as a part of their body. The tool becomes embodied, and with the new body comes a different perspective of the world and, in particular, its spatial layout.

That tools are embodied has been used to test the prediction that tool use affects spatial perception. From a methodological perspective, tools provide a fantastic test-bed for exploring whether a person's ability to act influences perception because the visual stimulus can be held constant while the perceiver's ability to act is systematically manipulated. For example, targets can be placed beyond arm's reach, but their reachability can be manipulated by giving the participant a reach-expanding tool (Witt et al., 2005). We found that the targets were judged to be closer when the participants used the tool than when they reached without the tool. This project was inspired by research showing that wielding tools affected neural coding of space and led to cross-modal interactions.

Research using single-cell neuronal recording methodologies showed brain-related changes when monkeys used a rake to reach for raisins (Iriki et al., 1996). The receptive fields of neurons in the parietal cortex elongated along the length of the rake. In other words, these neurons coded reachable space. As the monkey's ability to reach was impacted, these neurons adapted to the monkey's new abilities. In human studies on cross-modal interactions, research has shown that people are faster to detect a tactile vibration on their hand when a light is presented near the hand compared with when a light is presented far from the hand (Maravita et al., 2003). If the perceiver uses a tool that extends into the space of the far light's location, that light near the tool's end leads to similar cross-modal

interference as when the light was near the hand. The research showed embodiment of the tool and its effect on perceptual processes, including neuronal encoding and cross-modal interactions.

Tool-Use Affects Perceived Distance

I was a graduate student in the lab for Denny Proffitt at the University of Virginia when I read these studies of tool use on neural encoding and cross-modal interactions. At the time, the lab was starting to explore the effects of how the energetic costs to perform an action influenced perception of distance and slant (Bhalla & Proffitt, 1999; Proffitt et al., 1995, 2003). The tool research led me to question whether a person's ability to act, and the expanded repertoire due to tool use, would also influence the perception of distance. Denny and I brainstormed the study while in the conference room. We used Sweet 'N Low packets as targets and his conductor's baton as the tool. I judged the distance to the packets and estimated them as closer when I used his baton. And thus, our first study was designed. With the help of Ron Simmons in the shop, I set up a downward facing projector to project stimuli onto a large white platform that served as a table. White circles served as targets. The computer cued participants to either reach to the target or estimate its distance in inches. Participants performed one block of trials with a conductor's baton and one without the tool. I showed up in Denny's office shortly thereafter with a striking effect in my hand: participants had estimated the targets as closer when they used the baton than when they did not have a tool extending their reach. This was the first demonstration that a person's ability to act, rather than the energetic costs associated with action, influenced perceived distance. The research led us to claim that perception was action-specific; that perceivers see the world in relation to their ability to act. The research was also the first to demonstrate that tool use could affect spatial perception (Witt et al., 2005).

Subsequent research both expanded and refined the idea that tool use influences perceived distance. Tool use can affect perceived distance, but only when the tool expands reaching capabilities. When a short tool is used for which reach is hardly extended, perceived distance is unaffected (Osiurak

et al., 2012). Tool use seems to affect perceived distance, but only in younger adults and not in older adults (Costello et al., 2015), which may be due to less embodiment in older adults in general (Costello & Bloesch, 2017). Tool use could also affected perceived distance to targets presented in far space (10-30m) but only when the tool had an effect such as shining a laser (Davoli et al., 2012).

Perception Versus Judgments

The idea that using a tool could impact the perceptual experience of distance was controversial. Distance perception, and spatial perception in general, were thought to be functions primarily of the visual information, and no theories claimed a role for action. There were theories relating perception and action, but they did not emphasize a role for action in spatial perception. For example, Gibson stressed the importance of action, but considered the main function of perception to be the perception of possibilities for action, or affordances, rather than spatial perception (Gibson, 1979). Proponents of Gibson's ecological approach to visual perception adhered to the idea that perception is direct and thus a function of the incoming visual stimulation, rather than internal information about action (e.g., Lee et al., 2012). While perceivers could detect information about a tool directly (Turvey, 1996), this information should not influence visual perception because then it would be a demonstration of percept-percept couplings (cf, Epstein, 1982) rather than direct perception. Given the emphasis on perception of affordances, one proposal was that the impact of actions on spatial perception was actually a demonstration of how perceivers see affordances even when judging spatial properties such as distance (Fajen & Phillips, 2013).

As another example, the theory of two visual streams also emphasized action in perception (Milner & Goodale, 1995) but essentially discounted any role for action in the visual stream responsible for conscious perceptual experience and instead relegated action to the unconscious dorsal stream (Witt, 2018a). Other theories proposed a tight link between perception and action at the representational level (Hommel et al., 2001; Prinz, 1990), but this framework emphasized features (such

as left versus right) as being encoded in the representations, rather than perceived magnitude of spatial properties such as distance and speed.

With such a controversial claim that a person's ability to act could influence spatial perception came challenges to the claim that perception was affected as opposed to some other process. Initial challenges argued that the effects were due to response bias rather than genuine effects on perception (Durgin et al., 2009; Hutchinson & Loomis, 2006). Participants tend to want to be good subjects (Orne, 1982) and are willing to conform to experimenter expectations (Asch, 1955). Thus, participants may have seen the targets to be the same distance away but reported the ones that could be acted on as being closer.

Differentiating between perception and judgment-related processes such as those involved in response bias poses a challenge because perception is an internal state and thus cannot be observed directly. Instead, researchers observe judgments and behaviors and make inferences about the underlying perception. Strategies are necessary to resolve whether a given effect on perceptual judgments is due to an underlying difference in the perception or a difference in post-perceptual processes involved in generating the response (Philbeck & Witt, 2015).

One strategy to differentiate perceptual from judgment-based effects is the use of indirect measures. Indirect measures allow for inferences about the dimension of interest (in this case, distance perception) but do not explicitly measure it. For example, researchers can measure perceived size as an indirect measure of perceived distance. Perceived size is proportional to an object's retinal size and perceived distance, so if perceived distance decreases, perceived size should also decrease. In a series of studies using perceived size as an indirect measure of perceived distance, participants reached to targets beyond arm's reach with or without a tool, then estimated the size of targets. When they reached with the tool (or reached and used a laser pointer), they also estimated the targets to be smaller (Suh & Abrams, 2018). This pattern is consistent with the idea that the targets looked closer.

The studies on estimated size also took the important step of asking participants what they thought was the purpose of the experiment (Suh & Abrams, 2018). Only two out of the 96 participants responded that the experiment was about distance perception and the tool should make the target appear closer. That so few can even guess what the study is about poses a serious challenge to the claims that these effects are due to response bias. Participants cannot know how to alter their responses if they do not correctly guess the experiment's purpose.

Other indirect measures of perceived distance have also supported the idea that tool use can influence perceived distance. In one experiment, participants had to judge the shape of a triangle composed of three circles that was positioned such that the base circles were within reach and the apex circle was beyond reach (see Figure 1). If tool use affected perceived distance, the circle at the apex should appear closer, which should make the whole triangle look shorter. In one experiment, participants estimated the triangle shape by manipulating the shape of a second triangle presented on a computer monitor so that the two triangles had the same aspect ratio (see Figure 1). In a second experiment, participants viewed only the triangle on the table and adjusted the locations of the base circles to make the triangle equilateral with all three sides being the same length. After making these shape judgments, participants reached to the circle at the apex. They reached with the conductor's baton in one block and without it in another block of trials. Both experiments revealed that reaching with the baton made the triangle appear squatter than when reaching without the baton (Witt, 2011). This pattern is consistent with the idea that reaching with the tool made the apex circle appear closer, and thus made the triangle appear squatter.

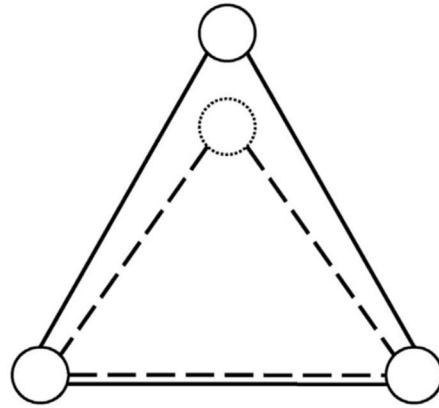


Figure 1. Experimental set-up for experiments on tool use and perceived shape (left panel). The participant estimated triangle shape by manipulating the shape of the triangle on the monitor to their right, then reached for the far circle with or without the tool. The hypothesized effect of seeing the target as closer (dotted circle) on perceived triangle shape (dashed lines) is to make the triangle appear squatter (right panel).

Intention, Observation, and Imagination

The studies on single-cell recordings had shown that the receptive fields only elongated when the monkey intended to use the rake but not when the monkey passively held the rake. To assess whether our effects on spatial perception also depended on actively using the tool, we ran a follow-up study. In the experiment, participants never reached toward the target; they only estimated the target's distance. During one block of trials, they held the conductor's baton but never used it. In this study, the presence of the tool did not impact perceived distance. Only when participants intended to use the tool did the tool affect perceived distance to the target (Witt et al., 2005). This and our other research on energetic demands (Witt et al., 2004, 2010) formed the basis for the claim that a person's intention to act was relevant for these action-specific effects on perception. This claim is contentious because in many studies on action-specific effects, participants never performed any actions. I could speculate (e.g., maybe the intention to walk is a default stance when viewing the ground plane and thus does not require explicit instructions to evoke an intention to act), but the fact of the matter is that this is an area

in need of more research. A challenge for this line of research is difficulty in knowing a person's intentional stance when no explicit instructions are given.

Summary

Reach-extending tools affect perceived distance to targets presented beyond arm's reach. Targets appear closer, as measured with direct measures of perceived distance and indirect measures such as perceived size, shape, and parallelism. The tool effect extends to far space when tools enable action in far space. The tool effect also extends to situations for which tool use is observed or imagined. These results speak to the underlying mechanism of the tool effect by showing that action's influence on perceived distance is not dependent on execution, per se, but possibly involves the processes involved in preparing the action and anticipating its consequences.

The Pong Effect

The tool effect showed the impact of a physical tool on perceived distance. We have also explored the impact of virtual tools on spatial perception. These investigations have involved a simplistic virtual tool: the paddle in a modified version of the classic computer game Pong. Participants attempted to block a ball that moved across the screen using a joystick to control the paddle (see Figure 2). We systematically manipulated their ability to block the ball by manipulating the size of the paddle. When the paddle was big, participants were successful approximately 95% of the time. When the paddle was small, success dropped to approximately 50%. After each attempt, participants estimated the speed of the ball. In some experiments, they estimated ball speed on a scale of one to seven. In other experiments, they performed a speed bisection task for which they estimated the ball as moving more like the slow anchor speed or more like the fast anchor speed, having been trained on the anchor speeds at the beginning of the experiment. In another experiment, they also saw a comparison ball moving at a constant speed, and they estimated which ball – the target or the comparison – moved faster in a visual comparison task. Regardless of the method by which they made their judgments, participants estimated

the ball as moving slower when it was easier to block than when it was harder to block (Witt & Sugovic, 2010, 2012). This difference in estimated speed between the small and big paddles is known as the Pong effect. The Pong effect is statistically robust and thus provides a useful experimental task for evaluating two important questions. The first is to determine whether the effect of using the virtual tool on perceptual judgments is truly a perceptual effect. If so, the second question is to determine the underlying mechanism. Much progress has been made on the first question; little progress has advanced the answer to the second question.



Figure 2. The original set-up for the Pong experiment. Participants controlled the paddle (white rectangle) with a joystick and attempted to block the ball (white circle). Later studies implemented the Pong task on a desktop computer.

A Perceptual Effect

Since the early pioneering work of Denny Proffitt and his students Makhul Bhalla and Jeanine Stefanucci (Bhalla & Proffitt, 1999; Proffitt et al., 1995, 2003), research has questioned whether a person's ability to act truly affects spatial perception (Durgin et al., 2009; Hutchinson & Loomis, 2006; Woods et al., 2009). In 2016, Firestone and Scholl outlined a small set of alternative explanations that, they argued, could explain all purported top-down effects on perception, including action-specific effects. These alternatives included response bias, judgment-related processes, effects of attention or memory, or unintended visual differences. They provided numerous examples from the action-specific

literature showing that these alternatives could explain the effects on perceptual judgments, thereby attempting to discredit claims that the results were due to perceptual effects. However, their examples were based on weak or non-robust action-specific effects. For example, the effect of dart throwing success on estimated target size is not a robust effect (Witt, 2017b), so evidence suggesting this effect is due to judgment-related processes (Wesp & Gasper, 2012) or memory-related processes (Blaesi & Bridgeman, 2015; Cooper et al., 2012) does not impale all claims regarding action's potential effect on perception.

There is an asymmetry in the evidence required to make claims for or against a perceptual effect. Only a single alternative explanation needs to be supported to prove that a given effect is *not* perceptual. But to prove that a person's ability to act could never affect perception requires proving alternative explanations for *all* possible action-specific effects. Conversely, to argue that a given action-specific effect is perceptual requires evidence against *all* possible alternative explanations. Merely proving that one alternative explanation is not responsible for the effect is insufficient to claim the effect is perceptual.

Perception cannot be measured directly, so evidence for a perceptual effect must come from proof-by-elimination. This requires systematically exploring all possible alternatives and testing each against a perceptual explanation. If even a single action-specific effect can withstand all these challenges, this is evidence that a person's ability to act *can* influence perception. The claim of a perceptual effect should not be generalized to other action-specific effects, but it does show that spatial vision can be affected by a person's potential for action.

The best way to assess whether a person's ability to act can influence perception is to pair the strongest arguments against a perceptual effect with the strongest action-specific effect. To achieve this, my students and I assembled the list of alternative explanations and painstakingly evaluated each one in the context of the Pong effect. In short, the evidence showed that the Pong effect is not due to

any of these alternative explanations, thereby building a strong case that the effect is truly perceptual (Witt, 2017a; Witt, Sugovic, Tenhundfeld, et al., 2016).

Response Bias. Response bias is one of the primary concerns with effects like action-specific effects. According to a response bias explanation, people see the speed of the ball similarly regardless of whether the paddle is small or big, but they respond that the ball is moving faster when the paddle is small because they infer the purpose of the task and conform to the task demands of the experiment. Task demands have always been a concern in perception research.

To explore the possibility of response bias in the Pong effect, we have employed many strategies. For example, in one experiment, grouped participants based on their compliancy with our set of instructions on how to estimate ball speed. The response bias account predicts that the Pong effect will emerge only in compliant participants and not in non-compliant participants. In contrast, the perceptual account predicts a Pong effect in both groups of participants. The data showed a similar Pong effect in both groups, which is consistent with a perceptual explanation and inconsistent with any role for response bias in the effect (Witt & Sugovic, 2013a). However, a confound is that the study did not differentiate compliancy with individual differences in perceived speed.

To test the role of response bias more directly, we implemented the strategy hailed by critics of the action-specific account, namely post-experiment questionnaires (Durgin et al., 2009; Chaz Firestone & Scholl, 2016). After completing the Pong task, participants were first asked an open-ended question about the purpose of the study (Witt et al., 2018). Approximately 25% mentioned something about paddle size and perceived ball speed, although all these participants also mentioned each of the other manipulated factors, including the irrelevant feature of whether the background had been rendered red or green. Nevertheless, these participants were labeled *discerning*. A later question asked participants to predict what factors might affect perceived speed, and another 25% indicated paddle size. These participants were labeled *suspicious*. The final question told participants the purpose of the study and

asked if they suspected as much. Those who said no were labeled *naïve*. We then compared the Pong effect within and across the groups. All three groups showed the Pong effect with no notable differences between them. Even participants who had no insight into the purpose of the experiment showed the Pong effect. This is a damning blow for the response bias account.

Next, we ran a second study that started by explicitly telling participants about the Pong effect and instructed them not to let their judgments be swayed by extraneous factors like the size of the paddle (Witt et al., 2018). This forewarning failed to eliminate the Pong effect, which emerged as strong as is typically found. The failure to eliminate or even reduce the Pong effect was not due to ineffective instructions; the instructions effectively eliminated the non-perceptual effect of the background color. In Experiment 1, when the background was red, participants had estimated balls moving faster than when the background was green. However, the instructions in Experiment 2 eliminated this effect of the background, which is not thought to be a perceptual effect. The instructions effectively eliminated response bias effects but did not eliminate the Pong effect, supporting the claim that the Pong effect is not due to response bias.

Judgments. Another alternative is that action-specific effects like the Pong effect are due to judgments, rather than perception. For example, when asked to judge ball speed, which is a hard task, participants instead estimated how hard it *felt* to block the ball. Several strategies have been used to differentiate judgments from perceptual processes. One strategy that was heavily endorsed by researchers skeptical of claims of perceptual effects is to use instructions to alter how the participant responds, with one set of instructions focusing on how the target *appears* and another set focusing on non-visual factors (Firestone & Scholl, 2016; Woods et al., 2009). We implemented this strategy in the Pong task and found significant Pong effects for both instruction groups (Laitin & Witt, 2020).

Another endorsed strategy is to use a cover story to explain away differences in performance (Firestone & Scholl, 2016; Philbeck & Witt, 2015; Wesp & Gasper, 2012). We found a cover story had no

impact on the Pong effect, but the cover story successfully eliminated a judgment-based effect that is also found in the Pong task. This judgment-based effect is called the *trial outcome effect*. Trial outcome refers to whether the participant successfully blocked the ball or missed it. After missing the ball, participants will sometimes rate the ball as going faster, as if to account for why they missed it, compared with when they successfully block it. This difference in estimated speed when the ball is missed versus blocked is the trial outcome effect. Given that the trial outcome occurs at the end of the trial and the ball is no longer moving (because it was blocked) or only travels a bit more before disappearing off the edge of the screen (when missed), there is little visual information about ball speed. Therefore, the trial outcome effect is assumed to be one of judgment rather than perception. That a cover story eliminated the trial outcome effect reveals the cover story was effective; that the cover story did not eliminate the Pong effect suggests the Pong effect is not due to judgments (Witt et al., 2017).

We have also implemented other strategies, such as giving explicit feedback on speed judgments to help reinforce the idea that we want participants to estimate speed and only speed. Such feedback did not eliminate the Pong effect, whereas a judgment-based account would have predicted elimination (King et al., 2018). The feedback did eliminate the trial outcome effect, showing the feedback was effective at eradicating judgment-based effects.

Implicit, Action-Based Measures. A favored strategy in perception research to differentiate perception from non-perceptual explanations is the use of implicit or action-based measures. We have done this by modifying the Pong task as follows. The ball (now rendered as a fish) moved horizontally across the screen. The paddle (now described as a net) was at the bottom of the screen. Participants pressed the joystick to release the net, which shot up in an attempt to catch the fish. After each attempt, the participant estimated the speed of the fish. Participants estimated the fish as moving faster when the net was small than when the net was big (Witt & Sugovic, 2013c).

The novel measure was to look, not just at the explicit estimations of fish speed, but at the timing by which participants released the net. If the fish truly looked like it was moving slower when the net was big, participants should have waited longer to release the big net than the small net. This is exactly what they did. A follow-up study explored, and subsequently ruled out, whether differences in net release time were due to differences in strategy to catch the fish, such as trying to catch the fish with the top part rather than the middle part of the big net. Although research has shown participants typically aim for the middle of targets (Trommershauser et al., 2003), we wanted to make sure our effect was not due to a difference in strategy.

To further drive home the point, we also ran a variation for which participants made no explicit speed judgments whatsoever. They simply tried to catch the fish on each trial for the entirety of the experiment. Here, too, we found a difference in net release time as a function of net size: they waited longer to release the big net compared with the small net (Witt, 2018b). Their actions signaled a difference in perceived speed as a function of the size of the net they were using.

The Pong effect has been run through the gauntlet of challenges to the claim that the effect represents genuine differences in perception. The outcomes have all pointed to the same conclusion: the perceiver's ability to act with the virtual tool influences perceived speed.

The Underlying Mechanism

That a tool, real or virtual, can influence spatial perception opens a new line of inquiry into what causes these effects. The answer must encompass two components. One is the source of the information about action, and the other is the process by which this source exerts its influence. Research on both these components are in their early stages.

Attention

A simple mechanism that would do little to challenge current theories of vision would be one of attention. In this scenario, wielding a tool and the corresponding changes to the person's ability to act

would result in their attention being directed in different ways to the target. These differences in attention would then lead to differences in spatial perception. According to this mechanism, action has no direct influence on perception but rather an indirect effect via attention. The data do not support this idea. In one experiment, we directed attention to the target by superimposing a secondary task on the target. The secondary task consisted of counting flashes presented on the fish while also trying to catch the fish with the net. Even when attention was equated by directing attention to the fish (and only including trials for which flashes were correctly counted), the size of the net still influenced both explicit speed judgments and net release time (Witt, Sugovic, & Dodd, 2016). Similar results were also found when attention was directed to the center of the screen. The Pong effect emerged regardless of how attention was directed.

Having ruled out a role for attention, we return to the two issues raised above: the source of information about the action and the process by which this source exerts its influence. The current literature on these two questions primarily involves the tool effect and the Pong effect, but other research will also be brought to address the issues.

The Source of Information about Action

The motor system anticipates the outcomes of an action via an internal, forward model that predicts what will happen (Wolpert et al., 1995). Because it was clear to me from some of my first experiments that the relevant information about action was about future or anticipated action, this mechanism appealed to me as a potential source of information about action that could lead to action-specific effects. Neuroimaging studies gave rise to the idea that these forward models might involve motor simulation for which many of the processes involved in action are conducted even in the absence of executing the action (Jeannerod, 2001).

Neuroimaging studies also showed that similar processes may be involved when imagining or observing the action as when executing it (Grezes & Decety, 2001). This led to the prediction that action-specific effects should also occur when imagining an action and when observing someone else perform the action. Several studies support this latter point. Watching another person reach with a tool led to judgments of targets appearing closer (Abrams & Weidler, 2015; Bloesch et al., 2012). Watching another person play the Pong game led to judgments of the ball as moving faster when the paddle was small than when it was big (Witt et al., 2012, 2014).

However, if action-specific effects are observed when watching another person, this raises the issue of whether *action* plays any role in these spatial biases. Indeed, several studies have shown spatial biases even when the perceiver did not or could not act. For example, in experiments on the perceived slant of stairs, participants who were fatigued reported the stairs as being steeper even when viewing life-sized images of stairs and thus could not physically interact with the stairs (Taylor-Covill & Eves, 2013).

A case can still be made for a role of action, however, if the action-related processes thought to evoke the spatial biases are still engaged in these other situations. Seeing a life-sized image of a staircase may initiate a forward model of what it would be like to climb the stairs had they been a real staircase. Seeing another person perform an action may initiate a forward model of what it would be like to reach with a tool or try to block the ball with the paddle. Indeed, prior research suggests that the perceiver sees the speed of the ball in relation to their own abilities to act, even when watching another person (Witt et al., 2014). Thus, the action-specific account is not necessarily specific to action execution but rather to the processes involved in anticipating action. Research is needed to determine the scenarios that engage these processes.

I have attempted to test the idea that forward models are involved in action-specific effects by using manipulations that purportedly interfere with the functioning of the forward model. The idea is

that if forward models are involved, this interference should eliminate the action-specific effect. For the tool effect, interference was formed by having participants squeeze a ball while making judgments of the distance to the target, then stopped squeezing to pick up the tool and reach. We found targets looked closer to participants who did not squeeze the ball compared with participants who squeezed the ball (Witt & Proffitt, 2008). However, these studies were severely underpowered, used the wrong statistical model specification, and with the correct model specification, were statistically significant only after removing outliers (Rohrer et al., 2021). Therefore, the studies must be replicated before drawing any corresponding conclusions.

In the Pong task, we attempted to interfere with the forward models by taking away control from the participant, either by freezing the paddle or using automation to take over the paddle (Tenhundfeld & Witt, 2020; Witt, 2017c). Although the results are somewhat consistent with a role for forward models, the evidence is mostly indirect. The role of forward models in action-specific effects will remain speculative until more sophisticated methodologies are developed to test the direct involvement of the forward models.

There have been some additional challenges to the notion that action is involved in these spatial biases because the same effects sometimes emerge even when simply watching the movement, such as when a computer controls the paddle in the Pong task. However, this literature is mixed and thus difficult to interpret. Watching a computer control the paddle eliminated the Pong effect in some cases and led to a full-sized Pong effect in other cases (Kirsch & Kunde, 2018; Witt et al., 2012). It should be noted that most of these studies were underpowered, particularly ones that conducted between-subjects comparisons. Low statistical power could potentially explain some of the discrepancies. It is also unclear the extent to which the underlying processes involved in action are also involved when observing a non-biological agent. For example, motor interference is observed when watching another person make incompatible movements but not when observing a robot (Kilner et al., 2003). In contrast,

the visual system is sensitive to when Fitts' Law (Fitts, 1954) is violated when observing both the actions of others and the actions of a robotic arm (Grosjean et al., 2007). In other words, the processes used to execute and observe actions can also be involved when observing computerized robots move. Thus, it is unclear whether finding a Pong effect when observing a computer is incompatible with a role for action in action-specific effects given that observing a computer can engage in action-related processes.

According to the action-specific account of perception, it is processes involved in anticipating action and its consequences that influence spatial perception. In which case, future research questions include determining the scenarios for which these processes are engaged and determining the mechanisms of these processes. As discussed above, one of the potential mechanisms is a forward model as described by Wolpert and colleagues (Wolpert et al., 1995). The processes underlying this model could be a kind of motor simulation (Grezes & Decety, 2001; Jeannerod, 2001), although they need not be.

Another alternative is a representation that codes both the action and the anticipated perceptual consequences, as has been described by the common coding approach (Hommel et al., 2001; Prinz, 1990). According to this framework, actions are represented not only by the movements themselves but also the perceptual consequences of the movements. These representations have often been described as encoding features (such as left versus right). Assuming these representations also code for the physical consequences, such as the energetic costs associated with the action, and code for magnitudes not just features, these representations could also serve as a potential source of information that influences spatial perception and leads to action-specific effects.

There may be multiple sources of information that lead to action-related spatial biases. Action-specific effects encompass several components of action including whether the action is possible (such as whether a target can be reached), whether the action is likely to lead to success (such as the probability that the ball will be blocked), the consequences if the action should fail (such as falling off a

cliff), and the energetic costs of performing the action (such as walking up a hill). These different components seem to have additive effects on spatial perception (Witt & Sugovic, 2013b). Thus, separate processes could be responsible for each aspect of action that influences spatial perception.

How Action Exerts its Influence

In addition to the need to determine the source of information about action, researchers must also determine how action exerts its influence on perception. One theory, known as the perceptual ruler account, asserts that a person's body and its ability to act fills the gap in transforming optical information – all of which takes the form of visual angles – into the spatial properties that are perceived such as size and distance (Proffitt & Linkenauger, 2013). The incoming visual information is in the units of visual angle, so the information must be transformed, and angles cannot use themselves to transform into something else. (Proffitt & Linkenauger, 2013) argued that this transformation must involve the body and its behavioral repertoire, suggesting no other solution is feasible. The feasibility of the perceptual ruler account has been debated (Firestone, 2013; Witt, 2015), but it is true that a feasible alternative has not been offered. Indeed, the body as a ruler to solve the problem of scaling visual angles to perceive distance was proposed by Berkeley (Berkeley, 1709, section XLV).

Others have argued that information about action serves as a multimodal source of information, just as audition or touch can influence vision (Witt & Riley, 2014). This proposal has recently gained traction with several demonstrations consistent with this proposal. For instance, in a virtual grasping experiment, the finger separation needed to grasp a virtual object was manipulated, and this impacted perceived size of the object (Kirsch et al., 2017; Kirsch & Kunde, 2019a). Furthermore, the influence of felt hand position on estimated size was related to the reliability of the visual and proprioceptive signals (Kirsch & Kunde, 2019c), as is predicted by a multisensory integration approach (Ernst et al., 2006; Ernst & Banks, 2002; Ernst & Bühlhoff, 2004). However, a critical question is how the motor system can

provide an estimation of, for example, object size even when the action has not yet been executed. One potential solution involves the outcome of motor planning. Indeed, planning to grasp the virtual object influences perceived size (Kirsch & Kunde, 2019b). Kirsch and Kunde (2019b) argue that planning involves activation of representations of the actions as well as their consequences, and that these representations can be involved in the multisensory integration. They speculate the source of these representations could be an internal forward model such as proposed by Wolpert and colleagues (Wolpert et al., 1995).

Tool Effects on Other Aspects of Perception

The primary focus of the chapter has been on how tool use affects spatial perception. Tool use also influences other aspects of perception. While detailing all these effects is beyond the scope of the chapter, a few will be briefly mentioned. In several studies, the focus has been on the idea that tools are incorporated into the body, and thus visual effects due to stimuli near the hands also occur when stimuli are presented near the tool. For example, cross-modal interactions for visual and tactile stimuli presented on and near the hand also occur when the visual stimuli are presented at the edge of the tool (Maravita & Iriki, 2004). As another example, visual attention is captured for stimuli presented near the hand (Abrams et al., 2008; Reed et al., 2006); for review see (Brockmole et al., 2013). These effects of visual attention near the hand also extend to stimuli presented at the edge of a tool (Reed et al., 2010).

An additional example of hand effects extending to tools comes from object identification tasks. Participants viewed photographs of hand-held objects such as hammers and teapots and made judgments, such as whether the object was right-side up or upside down. Prior research has shown faster judgments when the handle was oriented towards the responding hand (Tucker & Ellis, 1998). While there is debate regarding the replicability of the effect, the effect seems to be robust when participants consider the action that could be taken on the object, thereby leading to the priming of a response by the corresponding hand. When the objects are presented in far space such that they could

not be grasped, the effect of hand correspondence goes away, but the effect re-emerges when the participant holds a tool that extends into far space (Yang & Beilock, 2011).

A final example concerns the use of a specific tool, namely a gun, to identify the objects held by others. In the experiment, participants viewed photographs of a person holding either a gun or a neutral object, such as a shoe. The participant also held either a gun or a neutral object, such as a spatula. The task for the participant was to identify the object being held by the person in the photograph: if they saw a gun, they were to raise their object and point to the screen, and if they saw a neutral object, they were to lower their object and point to the ground. We measured both response time and accuracy. When the object shown in the photograph was a shoe, participants were slower and less accurate to identify it when the participants held a gun than when they held a spatula (Witt et al., 2020). Wielding a gun makes a person a shooter, and shooters had a harder time identifying non-guns in the photographs.

These studies reveal that tool use can influence many aspects of perception. It is unknown whether common mechanisms are involved in the effects of tools on spatial perception, visual attention, and object recognition, or whether these various influences represent different ways that tools affect perception.

Conclusions

Tools affect how the world looks. Tools change the action capabilities of a person, and with these changes come corresponding differences in visual perception. Tool use influences spatial perception – including perceived distance and perceived speed – as well as visual attention and object identification. Tools can be physical, imagined, observed, or virtual. The influence of tools on spatial perception builds on a long history of showing that tools are embodied and incorporated into one's body schema.

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