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# Limitations of distal effect anticipation when using tools

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A B S T R A C T

Modern technologies progressively create workplaces in which the execution of movements and the observation of their consequences are spatially separated. Challenging workplaces in which users act via technical equipment in a distant space include aviation, applied medical engineering and virtual reality. When using a tool, proprioceptive/tactile feedback from the moving hand (proximal action effect) and visual feedback from the moving effect point of the tool, such as the moving cursor on a display (the distal action effect) often do not correspond or are even in conflict. If proximal and distal feedback were equally important for controlling actions with tools, this discrepancy would be a constant source of interference. The human information processing system solves this problem by favoring the intended distal action effects while attenuating or ignoring proximal action effects. The study presents an overview of experiments aiming at the underlying motor and cognitive processes and the limitations of visual predominance in tool actions. The main findings are, that when transformations are in effect the awareness of one's own actions is quite low. This seems to be advantageous when using tools, as it allows for wide range of flexible sensorimotor adaptations and – may be more important – it evokes the feeling of being in control. Thus, the attenuation of perceiving one's own proximal action effects is an important precondition for using tools successfully. However, the ability to integrate discordant perception-action feedback has limits, especially, but not only, with complex transformations. When feature overlap between vision and proprioception is low, and when the existence of a transformation is obvious proximal action effects come to the fore and dominate action control in tool actions. In conclusion action–effect control plays an important role in understanding the constraints of the acquisition and application of tool transformations.



## 1. Introduction

Modern technology progressively creates workplaces that spatially separate movement execution from observation. When using tools, proprioceptive/tactile feedback from the moving hand (proximal action effect) and visual feedback of the movement in external space (distal action effect) do often not correspond or are even in conflict. Computer input devices are one example in this regard. For instance, the computer mouse makes a rather simple transformation. Hand movement on the horizontal table surface is transformed into cursor movement on the vertical display. Making the relationship somewhat less direct, a constant or variable gain factor applied to the hand movement perturbs the cursor movement. But still, the relationship between hand amplitude and cursor amplitude is obvious. In more sophisticated tools, like those used

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in aviation, applied medical engineering, and virtual reality, the relation can be quite complex and becomes less obvious. To operate rotary devices (e.g., a trackball) or force-sensitive devices (e.g., an isometric joystick), the agent has to learn an unfamiliar relation between an applied rotation or force (proximal effect) and a resulting cursor movement on the display (distal effect). In this case it is obvious to the agent that the visual feedback originates from transformed movements, and it is often observed that human movements become slow, inaccurate, and strenuous. The present paper focuses on basic understanding of the perception and action mechanisms in the use of tools with sensorimotor transformations. It provides a theoretical background and empirical evidence for the reciprocal influence of action on perception (e.g., Müsseler, 1999; O'Regan & Noë, 2001; Sutter, Müsseler, Bardos, Ballagas, & Borchers, 2008; in addition, an overview on cognitive representations of tool actions is provided by Massen (2013)).

The basic problem of integrating perception–action feedback is depicted in Fig. 1. In a human information processing system, sensorimotor transformations occur with various kinds of tool use. On the basis of the perceived body space and tool space a motor command is generated, which entails a movement of the corresponding effector. The bodily movement affects the tool and entails a tool movement. Thus, the human information processing system needs two feedback loops for processing movements with tools:

(1) The bodily movement is fed back to the perceived body space (via the proximal movement–effect loop shown as a dashed line). The loop receives its input from such sources as looking peripherally at one's own hands. Even when visual input is unavailable, tactile and proprioceptive perception from the moving hand contributes to the perceived body space. Body space does not have to correspond with the tool space (see below). It is widely accepted that the proximal movement–effect loop is essential for controlling human actions; moreover, that the anticipation of movement effects is used to generate an action plan from the very beginning. This so-called ideomotor principle of action planning holds that agents select, initiate and execute a movement by activating the anticipation of the sensory codes for the movement's effects (Greenwald, 1970; James, 1890; for an overview see Hommel, Müsseler, Aschersleben, & Prinz, 2001).

(2) To control tools successfully, the movement of the effective part of the tool (i.e., in most cases the intended action goal) also needs to be fed back to the agent (via the distal movement–effect loop, indicated with a dotted line). Often the tool does not transform the body movement into a tool movement in a one-to-one manner. Imagine a surgeon operating with a laparoscope inside a patient's body, inserting it through a tiny aperture. This modern surgical technique makes it easier for the patient to recover. But such benefits come along with challenges to the surgeon's motor skills and cognitive abilities. The instrument utilized in minimally invasive surgery functions like a two-sided lever, with the pivot point in the aperture of the patient's body. The relation between movements of the surgeon's hand outside the body and resulting movements of the effective part of the tool inside the patient is therefore rather complex. When the surgeon moves the hand leftwards, the tip of the tool inside the patient's body moves to the right (i.e., the "fulcrum effect"; Gallagher, McClure, McGuigan, Ritchie, & Sheehy, 1998). This inverse transformation is likely to contribute to more tissue damage than in open surgery (Savader, Lillemoe, & Prescott, 1997); it also affects the time to initiate a movement (Kunde, Müsseler, & Heuer, 2007; Müsseler, Kunde, Gausepohl, & Heuer, 2008). The second main feature of this lever transformation is the gain; that is, the relation between the movement amplitude of the hand and the movement amplitude of the tip of the lever. For translational movements (moving the lever back and forth through the pivot point) there is a constant gain of 1. But for rotations (moving the tip of the lever sideways or up and down) the gain is variable, depending on the ratio of the lengths of the load arm and the effort arm (gain anisotropy). Third, the surgeon receives visual feedback on a display somewhere in the operating theater, which is often not spatially aligned either with the surgeon's hand or with the tip of the tool.

The control cycles in Fig. 1 are omnipresent in technical environments, for instance, at computer work stations or when driving a car. Some sensorimotor transformations are easy to perform and occasionally we are even not

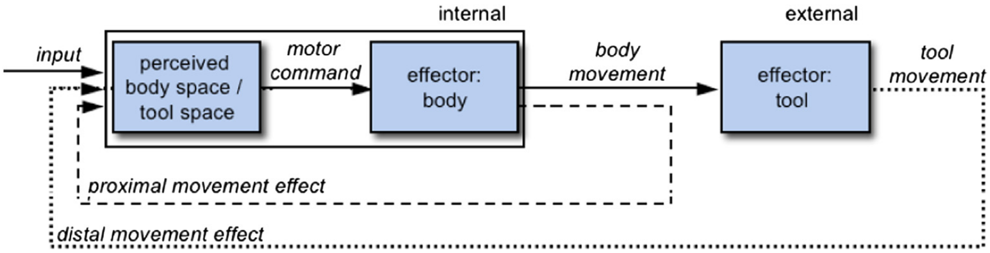


**Fig. 1.** Tool use requires coordination between proximal movement effects (proprioceptive/tactile feedback from the moving hand) and distal movement effects (visually display movements of the cursor or the tip of the tool).