Transportation Research Part F 59 (2018) 115–123

Contents lists available at ScienceDirect

Transportation Research Part F

journal homepage: www.elsevier.com/locate/trf

Sensorimotor adaptation when steering with altered vehicle dynamics ☆

Kristen L. Macuga *

Department of Psychological and Brain Sciences, University of California, Santa Barbara, United States

A R T I C L E   I N F O

Article history:
Received 11 May 2017
Received in revised form 3 August 2018
Accepted 28 August 2018

Keywords:
Driver behavior
Motor learning
Perception-action
Perceptual-motor performance
Virtual environments

A B S T R A C T

Though adaptive sensorimotor processes have been studied for simple, laboratory tasks such as reaching, less is known about how they might function during complex, real-world behaviors such as steering. The effects of altered vehicle dynamics on steering were investigated, using a physically moving electric vehicle outfitted with a portable virtual reality system. Vehicle dynamics were manipulated via changes in steering gain. Three groups of participants attempted to steer a series of curving paths with a lower steering gain, a higher steering gain, or a reversed steering gain. This adaptation phase was compared with pre-adaptation and post-adaptation phases, for which the steering gain was unaltered. As drivers accrued experience with the altered steering gains, they became more accurate and fluent in steering a vehicle. Adaptation to subtler steering gain changes was rapid, and without aftereffects, but adaptation to a more extreme steering gain (i.e., reversed) was slower, with aftereffects upon the initial return to the unaltered gain in the post-adaptation phase. Drivers can adapt relatively quickly to changes in steering gain, incorporating the relevant dynamics of the vehicle. The approach developed here could be used to refine theories of sensorimotor adaptation in the context of more practical applications, such as real-world human-tool systems.

1. Introduction

Athletes need to learn the correspondence between the forces applied to their baseball bat, tennis racket, golf club, hockey stick, or skis, and the resulting actions. Similarly, drivers should be able to internalize the relationship between the motion of the steering wheel and the corresponding motion of a new vehicle. In many instances, sensory feedback is sufficient for steering a vehicle. However, anticipating future vehicle actions may allow for more effective and stable steering control, particularly when sensory information is briefly absent or degraded. Internal models have been utilized in the literature on motor control to account for performance accuracy despite sensory delays and noisy signals (Jordan, 1995; Kawato, 1999; Miall & Wolpert, 1996; Wolpert, 1997; Wolpert & Flanagan, 2001; Wolpert, Ghahramani, & Jordan, 1995), though the tasks that have been studied involve laboratory studies on simple behaviors such as reaching. The goal of the current study was to examine these concepts in the context of complex, real-world behavior, specifically, how drivers respond to changes in vehicle steering dynamics. Having an internal model is having knowledge of the mapping between motor commands and their sensory consequences. Internal models represent the dynamics of a controlled system to predict

☆ This research was supported in part by AFOSR grant F49620-02-1-0145.
* Address: School of Psychological Science, Oregon State University, Corvallis, OR 97331, United States.
E-mail address: Kristen.Macuga@oregonstate.edu

https://doi.org/10.1016/j.trf.2018.08.018
1369-8478/

that system's behavior. They can be used to anticipate the sensory outcomes of motor actions (e.g., mimic the behavior of the system in order to predict future position and velocity given the previous position and velocity as well as the motor command sent to the muscles, essentially providing internal feedback of the predicted sensory information before it is actually available). Such anticipation helps to stabilize a system especially when sensory feedback is delayed or noisy. Internal models could be applied to vehicle steering control (Loomis & Beall, 1998, 2004) as such: If a driver has internalized the dynamics or handling characteristics of a vehicle, that driver should be able to steer more efficiently and effectively, especially in more difficult conditions. For example, if you own a sports car, you learn how that car responds to your control inputs. If you were to switch to a large truck, it would have very different dynamics. Your internal model of the sports car would be inappropriate for the truck, though presumably this internal model can be recalibrated over time. To internalize the vehicle dynamics, the driver needs to monitor both control inputs (turning of the wheel) and sensory feedback about how the vehicle moves given such control inputs.

The characteristics of internal models have been investigated using sensorimotor perturbations. Research involving the perturbation of dynamics has focused primarily on arm movements. Lackner and DiZio (2005) studied adaptation to altered dynamics (perturbed with Coriolis forces) in the realm of arm movements and tool use. Shadmehr and Mussa-Ivaldi (1994) and Conditt, Gandolfo, and Mussa-Ivaldi (1997) examined adaptation of arm movements in the presence of an externally imposed force field. Rieger, Knoblich, and Prinz (2005) and Krakauer, Ghilardi, and Ghez (1999) incorporated perturbations of both perceptual cues and dynamics. These experiments demonstrated adaptation to the altered conditions followed by aftereffects upon return to the initial conditions. Thus, there is substantial evidence that adaptation and aftereffects occur for the sensorimotor system that controls arm movements, indicating that the sensorimotor system adjusts to changes in dynamics by constructing and recalibrating an internal model of those dynamics. There is also some evidence suggesting that the system that controls locomotion may also be adaptable (Reisman, Block, & Bastian, 2005). Locomotor adaptation to sensorimotor mismatches can alter subsequent walking, without vision, to previously viewed targets (Durgin et al., 2005; Kunz, Creem-Regehr, & Thompson, 2013; Mohler et al., 2007; Rieser, Pick, Ashmead, & Garing, 1995). In the present study, I adopted a similar method, in which I removed visual feedback of a previously viewed path, to assess vehicle steering adaptation.

Researchers have also begun to investigate the nature of internal models for controlling systems including objects or tools. Dingwell, Mah, and Mussa-Ivaldi (2002) had participants learn to control simulated mass-spring objects in order to reach to a target, and found that they could form an internal model of the object's dynamics as evidenced by adaptation of reaching to compensate for the object's dynamics as well as aftereffects when the object was removed on catch trials. Adaptation can even happen without participants' conscious awareness of the sensorimotor perturbations that have been applied, as demonstrated by tool use studies involving circle drawing tasks (Knoblich & Kircher, 2004; Müsseler & Sutter, 2009; Sutter, Sülzenbrück, Rieger, & Müsseler, 2013). Imamizu et al. (2000) reported cerebellar activations related to the acquisition of an internal model of a new tool (computer mouse-controlled cursor) using fMRI. Though these adaptive processes have been demonstrated for simple, laboratory tasks such as reaching or drawing with a tool, much less is known about how they might function during more complex human-tool system behaviors such as vehicle steering. In a fixed-base simulator, Cunningham, Chatziastros, von der Heyde, and Bulthoff (2001) investigated adaptation to temporally delayed visual feedback. They found that participants were able to adapt to the temporal delays such that their performance improved with practice. Then, they showed aftereffects upon the removal of the delays such that performance in the original non-delayed condition was worse than performance during the pretest. Using a projection screen and foot pedal, Fajen (2005, 2007) examined adaptation in the context of braking. He manipulated brake strength and found that participants showed adaptation to the new brake strength and aftereffects upon return to the neutral brake strength. Thus, participants were not just relying on visual cues, but took brake dynamics into account, and continued to use the learned dynamics after the brake strength was returned back to neutral. These aftereffects disappeared shortly after however, indicating fairly rapid recalibration.

The aim of the present study was to investigate adaptations to changes in steering dynamics in the context of actual driving, with full visual, inertial (vestibular and somatosensory cues that accompany vehicle motion), and proprioceptive (turning of the steering wheel) feedback. Steering systems that can adaptively change steering gains based on the driver's control input and the vehicle's speed are starting to be adopted by some automobile manufacturers to increase maneuverability, reduce driver fatigue, or assist drivers with limitations in terms of strength or mobility. Therefore, knowing how drivers might adapt to these types of systems has practical relevance as well. The task of steering a real vehicle offers an ideal experimental paradigm for examining sensorimotor adaptation. It is a complex, highly familiar task where the steering control inputs and vehicle trajectories can be efficiently recorded and analyzed. It combines the precisely controlled conditions of psychophysical experiments with the more ecologically relevant active control behaviors. Furthermore, using a custom designed vehicle, I was able to selectively manipulate steering gain in order to investigate adaptive responses to changes in vehicle dynamics. The experimental apparatus, an electric vehicle equipped with virtual reality and a steering actuator, enabled manipulation of gain, such that the relationship between steering wheel movement and vehicle motion was not always consistent. The critical manipulation in the present study thus involved adjusting how the vehicle physically moved with respect to steering wheel inputs in order to examine how internal models are adapted in response to changes in steering gain. Steering gain is the ratio between the turn rate of the vehicle and the steering wheel movement (i.e., a high gain means that the vehicle turns quickly compared to the movement of the steering wheel, and a low gain means that the vehicle turns slowly compared to the movement of the steering wheel). I selectively altered these steering gains in order to characterize how drivers adapt to such changes. For example, think about learning how to drive a sports car, switching to