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An Affordance-Based Approach to Visually Guided Overtaking

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When an automobile driver overtakes a lead vehicle while avoiding oncoming traffic, does he or she do so with reference to the limits of his or her car? We investigated overtaking from the perspective of the theory of affordances. We define the *overtake-ability* affordance as a ratio of the minimum satisfying velocity required for safe overtaking (*MSV*) to the maximum velocity of the driver's car (V_{max}). Two groups of participants performed overtaking maneuvers, if deemed possible, by driving either a slow ($V_{max} = 25$ m/s) or a fast ($V_{max} = 32.5$ m/s) virtual

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car in overtaking situations constrained by 14 values of *MSV*. For any given *MSV* condition, participants in the fast car group were more likely to attempt an overtaking maneuver. However, when *MSV* was expressed in intrinsic units as a ratio of V_{max} for both groups, the frequency of overtaking was not significantly different across groups. Furthermore, overtaking frequency dropped to near 0% for both groups when *MSV* exceeded V_{max}. In accordance with the affordance-based framework (Fajen, 2007), our results suggest that participants select their overtaking maneuvers by perceiving an *overtake-ability* affordance.

As people navigate through the world, they make many decisions (some with life-or-death consequences) that require them to be accurately attuned to their physical capabilities. Even a maneuver as common as attempting to overtake a car could prove to be fatal if the driver misjudges his or her ability to pass the lead car before reaching oncoming traffic. In 2011, the French Interministry National Observatory for Road Safety reported that 12.71% of fatal automobile injuries in France occurred when drivers attempted to overtake a lead car by driving in the opposite lane (Observatoire National Interministériel de la Sécurité Routière, 2013, p. 69), highlighting the difficulty of this task and the consequences of failure.

We identify five phases of a basic overtaking maneuver, which we describe here using terminology that would apply in countries with right-side traffic. The process begins with the Start phase, during which the driver performs actions intended to help decide whether it is both legal and safe to initiate an overtaking maneuver, such as executing small lateral excursions in the opposite lane to improve viewing of the oncoming traffic. If the driver judges that conditions are safe enough to initiate an overtaking maneuver, he or she may then initiate a full lateral excursion into the opposite lane (Left phase) while accelerating if necessary to pass the lead car (Pass phase). Once the driver has visually verified that the lead car is now behind, he or she must return to the driving lane (Right phase) and end the overtaking maneuver (End phase).

Research in real-world (Clarke, Ward, & Jones, 1998; Wilson & Best, 1982) and laboratory (Gordon & Mast, 1970; Gray & Regan, 2005) conditions suggests that 14% to 68% of overtaking accidents are due to errors that occur during the Start phase when drivers judge whether to perform an overtaking maneuver. One of the aims of this study is to better understand the process underlying both the selection of an overtaking maneuver and its regulation. In an effort to clarify the causes of overtaking accidents, we consider the possibility that errors in deciding whether to initiate an overtaking maneuver can be attributed to difficulty in scaling the requirements for overtaking to the capabilities of the driven car.

The notion that drivers must decide if their own car's capabilities are sufficient given the requirements to overtake was proposed by Gray and Regan (2005). They reproduced overtaking situations in a fixed-base driving simulator and hypothesized that drivers should perceive the Time Required for Overtake (*TRO*;

computed from the lead car speed and position, participant's driving speed, and driver's car dynamics model) and compare it with the Time To Collision of the oncoming car (*TTC*) to judge if overtaking is safe. If $TTC - TRO > 0$, then overtaking is safe; otherwise overtaking is unsafe and any attempt to overtake will result in collision with the lead or oncoming car. They found that drivers mainly decided to overtake when $TTC - TRO > 0$ but also that drivers continued to overtake when $TTC - TRO < 0$ on up to 16% of trials. Those errors were interpreted as either errors in drivers' perception of their action boundaries when estimating *TRO* or as difficulty in the initiation of the overtaking maneuver at a constant critical distance or time from the lead car.

$TTC - TRO$ specifies whether overtaking is possible as well as the margin for error in the temporal domain. However, it is not informative about the range of velocities that would bring about a successful overtaking maneuver. In other words, if drivers relied on $TTC - TRO$, they would not be able to perceive when overtaking is possible by traveling at some speed below their maximum speed (e.g., 75% of maximum speed) or the minimum percentage of their car's maximum speed that is required to successfully overtake. This is arguably more important than $TTC - TRO$ because drivers may need to compensate for unexpected events, such as a sudden headwind or an increase in speed of the lead or oncoming car. If drivers could perceive the minimum percentage of their car's maximum speed that is required to overtake, they would know before initiating the overtaking maneuver whether they would have the ability to further increase their speed to compensate for unexpected events.

In this study, we approach the overtaking task as a problem that involves the perception of "action-scaled" affordances, which are possibilities for actions defined by dimensions of the environment taken with respect to the agent's action capabilities. The ability to perceive action-scaled affordances has received increasing attention since Gibson's (1977) formulation of the theory of affordances. Researchers have investigated the perception of the "*catch-ability*" of fly balls (Fajen, Diaz, & Cramer, 2011; Oudejans, Michaels, Bakker, & Dolné, 1996), "*avoid-ability*" of a collision by braking (Fajen, 2005a, 2005b, 2005c; Fajen & Devaney, 2006), and "*pass-ability*" of a shrinking gap between converging obstacles (Fajen & Matthis, 2011) by showing that relevant properties of environment are perceived in relation to the kinematic characteristics of the body or one's vehicle. From this perspective, the selection of appropriate actions entails a scaling of properties of the environment (e.g., speed needed to catch a fly ball) by one's action capabilities (e.g., maximum running speed).

Just as the selection of actions that are appropriately gauged to one's capabilities relies on the perception of affordances, so does the continuous regulation of movement based on optical information (Fajen, 2005b, 2007). By this account, actors adjust their current behavior so as to keep the state needed to successfully complete the action within the range of possible states that are defined by the actor's capabilities. In the case of running to catch a fly ball, such a strategy entails adjusting running speed so as to keep the speed needed to catch the ball within a "safe" region between zero and the fielder's maximum possible running speed. Satisfying this requirement ensures that the action remains possible within the actor's limits. If the state needed to perform the task exceeds the actor's capabilities, then the task is no longer possible and a new action mode must be selected.

Let us apply the same logic to the overtaking task. First, we identify the two key variables that determine when overtaking is (and is not) possible within the capabilities of the driver's car: (a) minimum satisfying velocity (*MSV*), which we define as the minimum velocity required to overtake the lead car without colliding with the oncoming traffic, and (b) maximum velocity (V_{max}), which is the maximum possible speed of the driver's vehicle. The ratio of these two variables determines whether overtaking is possible. Specifically, if $MSV/V_{max} \leq 1$, it is physically possible to overtake the lead car because the minimum velocity required to overtake (*MSV*) is less than or equal to the velocity that the driver is capable of moving (V_{max}). Conversely, if $MSV/V_{max} > 1$, overtaking is not possible even by traveling at the car's maximum velocity. In that case, the driver is obliged to follow the lead car in the right lane until the oncoming car passes. Thus, the point at which *MSV* is equal to V_{max} defines an action boundary that separates situations in which it is still within the driver's capabilities to overtake from situations in which it is no longer possible to overtake.

In this study, two groups of experienced drivers were instructed to perform overtaking maneuvers, if deemed possible, in a driving simulator. The maximum velocity V_{max} of the participants' virtual car was manipulated as a between-subjects variable. The *MSV* at the beginning of each trial was manipulated as within-subjects variable such that overtaking was possible on some trials and impossible on others, depending on whether *MSV* was greater than or less than V_{max}. If decisions about whether to overtake are based on the perception of *overtake-ability*, and if participants are sensitive to the limits of their virtual car, then they should choose to overtake when *MSV* is less than V_{max} (by a sufficient margin to allow for some error in the perception of *MSV*) and choose to follow rather than overtake the lead vehicle when *MSV* is greater than V_{max}.

METHODS

Participants

Sixteen experienced drivers (13 men, 3 women), 26.2 ± 4.9 years of age, all of whom held a driving license for 7.1 ± 4.1 years, took part in the experiment. All had normal or corrected-to-normal vision. They were not informed about the purpose of the study. A local ethics committee approved the experimental protocol.

Apparatus

The fixed-base driving simulator used in this experiment is illustrated in Figure 1. Participants sat in a playseat (Mobsim) and used their right foot to manipulate two spring-loaded pedals (Trackstar 6000 GTS, Extreme Competition Controls Inc.) and their hands to manipulate a steering wheel (Trackstar 6000 GTS, Extreme Competition Controls Inc., Minneapolis, MN). The data from the pedals and steering wheel were sent to a PC via a USB port. These data were used by an OpenGL custom-made virtual reality application (Imagine Create & Experiment, a software package developed at the Institute of Movement Sciences, Marseille, France) to control the torque and the direction of the wheels of a virtual car. The virtual scene from the driver's viewpoint was rendered stereoscopically at a frame rate of 75 Hz in a head-mounted display (Hi-res 900 stereo, Cybermind Corp.). An electromagnetic tracking system (6 DoF Flock of Birds, Ascension Technology Corp., Burlington, VT) linked the driver's viewpoint in the virtual

FIGURE 1 Overview of the setup. Participants sat on a playseat integrated into an aluminum frame and wore a head-mounted display. They controlled the velocity of the virtual car with accelerator and brake pedals and lateral excursions between lanes with the steering wheel. Participants' head pitch, yaw, and roll orientations were measured with an electromagnetic tracker and coupled to the visual scene. Participants could also display rear mirrors by pressing buttons on the steering wheel.

world with rotations of the head while maintaining the position of observation at 0.975 m above the ground in the center of the driver's virtual seat. Two lateral buttons, located on the left- and right-hand sides of the steering wheel, and a central button could be pressed to momentarily display side and/or center rearview mirrors.

Virtual Environment

The virtual environment depicted in Figure 2 was constructed so that road marking, road dimensions, and car appearance conformed to the French regulations. The visual scene included the car's hood, rear-side mirrors (i.e., left, right, and central mirrors, when fixated and activated), a randomly rotated background composed of a blue lighted sky with mountains, a cement-textured rectilinear two-way road (2,500 m long × 2 lanes × 3.50 m lane width), two superimposed white continuous lines defining the road's left and right edges, a white discontinuous line separating the two single lanes, and three cars (i.e., lead, participant, and obstacle cars) measuring 4.415 m long × 1.740 m wide × 1.475 m high. In addition, a hatched-textured starting line (5 m long) crossed the two lanes and marked the start of the 300 m long experimental driving zone, and a hatched-textured ending line marked its end.

The lead car drove in the right lane and the obstacle car was in the left lane and remained immobile. The decision to use an immobile obstacle car was motivated by our aim to determine if collisions during overtaking are due to a failure to properly perceive the overtaking requirement in relation to the speed capabilities of one's car. If the obstacle car were moving, then it would have been impossible to determine whether any difficulties with the overtaking task were due to a failure to properly scale the *MSV* to the car's maximum speed capabilities or a misperception of the approach speed of the oncoming car. In other words, keeping the obstacle car stationary helped to isolate any possible effects of miscalibration to one's speed capabilities. Although the overtaking task is often performed with an approaching obstacle car, it is not uncommon to encounter stationary obstacles in the passing lane. Many single-lane roads have temporary passing lanes that open up to two-lane roads for a short stretch to allow for passing. Similarly, when the passing lane on a highway is closed due to road construction, construction crews will sometimes place a stationary vehicle at the beginning of the lane closure. Thus, it is not uncommon for drivers to encounter situations in which they must decide whether to overtake a lead vehicle in the left lane and return to the right lane before reaching a stationary obstacle. The obstacle car was fully visible at the beginning of each trial.

Because there was no speedometer, participants' perception of velocity was based on optical flow and on auditory feedback played through a set of loudspeakers that increased the frequency of the engine sound with participants'

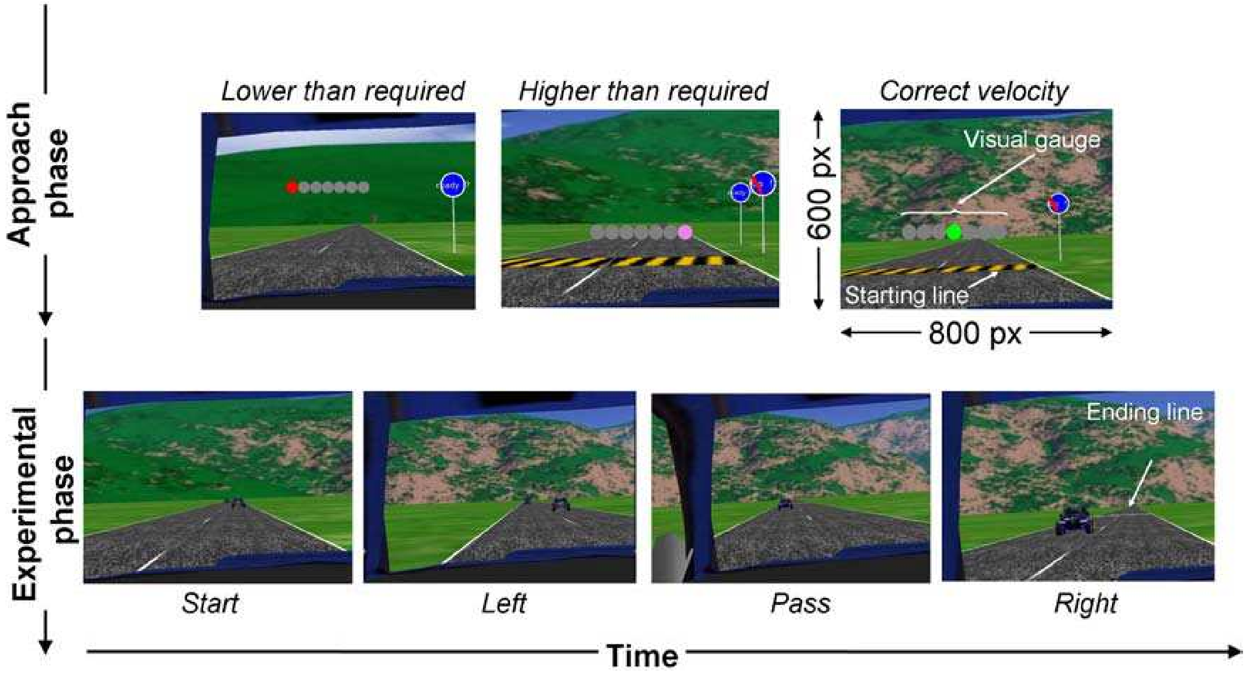

FIGURE 2 Screenshots of the virtual scenes during the approach (top) and the Start, Left, Pass, and Right phases of an overtaking maneuver performed during the experimental session (bottom). During the approach phase, there was visual gauge consisting of seven initially gray circles that changed color to indicate the participant's compliance with the trial's initial velocity requirements. Red circles on the left and blue circles on the right indicated that the participant's velocity was below or above the target velocity, respectively, and the green circle in the middle indicated that the participant was in compliance.

car velocity. The volume of the engine sound was kept constant across the experiment. No auditory feedback was provided about the lead or obstacle car's engine noise. A visual gauge, which was used to ensure that participants matched initial task requirements (see next subsection), was displayed in the upper middle portion of the screen before each trial.

Dynamics of the Participant's Virtual Car

Participants adjusted the velocity of their virtual cars by pushing and releasing the accelerator and brake pedals, which in turn generated accelerative or decelerative torque that was applied to the wheels of the car's dynamical model. The torque generated by the accelerator ($torque_{acc}$) was determined by the following Equation (1):

$$torque_{acc} = (V_C < V_{max}) \cdot (K \cdot (pedal_{acc} \cdot V_{max} - V_C)) \tag{1}$$

where V_c is the current car's velocity; $pedal_{acc}$ is the pedal's position ranging from 0 to 1; and K is a constant lag coefficient, which we set to 0.9 to apply realistic $torque_{acc}$. $V_C < V_{max}$ was equal to 1 when $V_C < V_{max}$ and 0 when $V_C = V_{\mathrm{max}}$, which ensured that no accelerative torque was applied when the car was traveling at its maximum speed.

The decelerative torque generated by the brake pedal was determined by Equation (2):

$$torque_{decc} = (V_C > 0) \cdot (J \cdot (pedal_{dec} \cdot D_{max})) \tag{2}$$

where $pedal_{dec}$ is the brake pedal's position ranging from 0 to 1, J was set to 3 to apply realistic $torque_{decc}$, and D_{max} is the maximum deceleration of the virtual car always set to $-15\,\mathrm{m/s}^2$. This allowed the slow and fast cars to stop from their V_{max} in about 2 and 2.33 s, respectively. $V_C > 0$ was equal to 1 when the car was moving and 0 when it was stationary.

The accelerative and decelerative torques were fed into a physics engine (PhysX™, NVIDIA®), which determined the virtual car's velocity given the driver's commands together with resistance forces (e.g., air, rolling friction) and the car's properties (e.g., mass, damping, wheel radius). This allowed for more realistic behavior than would be possible if pedal positions were mapped directly to car velocity.

Participants controlled the initiation of lateral excursion between lanes by turning the steering wheel more than ± 30°. The first counterclockwise turn of the steering wheel beyond this threshold triggered a sigmoid-shaped lateral excursion from the right lane to the left lane. A subsequent clockwise turn moved the car from the left lane to the right lane. When initiating a lateral excursion on lane, the velocity of the car was kept constant during the curvilinear segments of the sigmoid trajectory. Participants were able to adjust car speed during the brief period of linear motion between the two curvilinear segments. However, the linear segment was very brief and any speed changes were negligible. The rate of change in heading during the lane change was preprogrammed and independent of the car's velocity. As such, the distance that the car traveled and the time spent during lane change varied from 36 to 48 m and from 1.1 to 1.5 s when the velocity of the car ranged from 5 to 25 m/s, respectively. When the car was not changing lanes, it was constrained to move within the lane.

Procedure

The experiment consisted of two sessions, which we refer to as the *familiarization session* and *experimental session*. The familiarization session was designed to allow participants to familiarize themselves with the experimental task, controls, and setup as well as the key events that occurred during a trial. Each trial began with an approach phase in which participants attempted to match a target velocity using the visual gauge (Figure 2). The approach phase ended when participants passed the starting line at a target velocity (i.e., the MSV^{start} conditions ± 10%; see next subsection). When the participants' velocity matched this requirement, the visual gauge disappeared, the lead and obstacle cars appeared, and participants' behavior was unrestricted. Otherwise, the starting line moved 50 m farther and the approach phase started again. After the end of the approach phase, participants practiced overtaking the lead vehicle if deemed possible. With this setup, participants' velocity at the start of the trial was always equal to the MSV^{start} for that trial, except when the MSV^{start} exceeded V_{max}. In this case, participants' velocity was equal to V_{max}. Participants were also encouraged to explore the capabilities of their cars, including maximum velocity and braking, during this phase. They were asked to monitor the behavior of the surrounding cars by using the side rearview mirrors (i.e., before starting an overtaking maneuver and when cutting off the lead car trajectory). The familiarization session ended after one repetition of each of the 14 experimental conditions (see next subsection) presented in an ascending order. None of the participants reported having any difficulties controlling their cars at the end of the familiarization session.

The experimental session started after the familiarization session and a short rest period. Experimental trials were identical to those experienced during the familiarization session. However, participants were reminded that during the experimental session, they should attempt to reach the finish line as soon as possible while absolutely avoiding collisions as in a real driving situation. The time spent by participants from the starting line to the ending line was provided as a feedback to participants. The experimental session lasted approximately 1 hr per participant. Short rests were given regularly according to participants' individual requests.

Independent Variables

Our approach to the question of whether drivers are properly attuned to the limits of their car during overtaking was to investigate the influence of the car's maximum velocity on the perception of safe overtaking possibilities. As such, we manipulated the car's maximum velocity (V_{max}) as a between-participants variable with two levels (25 and 32.5 m/s). Participants were thus divided into two groups of mixed genders. Half of the participants were assigned to the *slow* virtual car condition with $V_{max} = 25$ m/s and the other half to a *fast* virtual car condition with $V_{max} = 32.5$ m/s. We manipulated the *MSV* at the start of each trial (MSV^{start}) as a within-participants variable with 14 values ranging from 2.5 to 32.5 m/s in 2.5 m/s increments. *MSV* was calculated as the quotient of two values d_S and $t_{overtaking}$. d_S is the length of the trajectory that a participant's car *S* must follow to move from its current location to a location in the right lane with its front bumper aligned with the front bumper of the obstacle car *O*. The calculation of d_S included not only the distance that the participant's car traveled parallel to the road but also the lateral distance traveled during lane changing. $t_{overtaking}$ is the amount of time remaining until the lead car reaches the location where its front bumper is just behind the rear bumper of S at the end of overtaking (Figure 3).

This yielded 14 MSV^{start}/V_{max} ratios ranging from 10% to 140% for the slow car and from 7.69% to 107.69% for the fast car. The distance at which the lead and obstacle cars appeared at the start of the trial (as measured from the center of cars) remained constant over the experiment. The velocity of the lead car remained constant during a trial but was varied across conditions to be always equal to half of the MSV^{start} value. The obstacle car remained immobile in the left lane of the road. Details of the construction of experimental conditions are reported in Table 1. Two trials during which a car overtook the participant's car in the left lane were added to randomly chosen MSV^{start} conditions for each participant. This discouraged participants from systematically initiating an overtaking maneuver at the start of the trial without checking their rearview mirrors. The resulting 16 trials were presented in random order into blocks that were repeated five times, resulting in a total of 80 trials.

Dependent Variables

Analyses focused on the frequency of collision, the selection of driving maneuver, and velocity regulation during the overtaking maneuver.

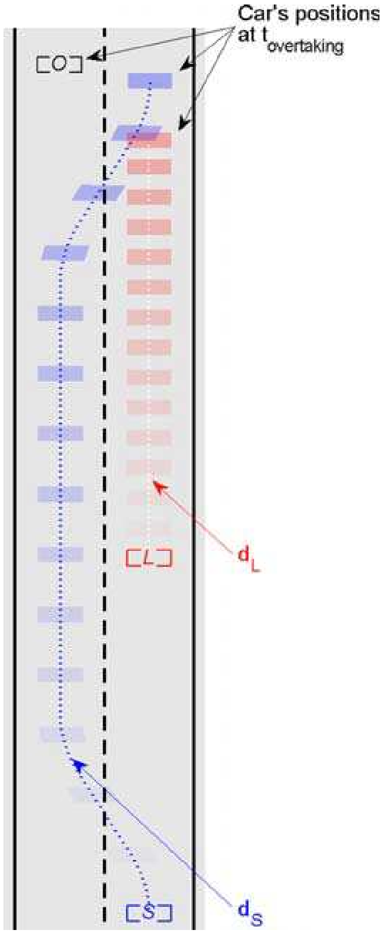

FIGURE 3 Numerical simulations of participant's (*S*) and lead (*L*) car's trajectories when traveling the distance d_S and d_L during the MSV^{start} condition equal to 32.5 m/s. Successive current positions of *S* and *L* cars are displayed every 40 ms whereas the obstacle car (*O*) remains immobile. $t_{overtaking}$ occurs when the front bumper of *S* is aligned with the front bumper of *O* while the front bumper of *L* is just behind the rear bumper of *S*. Axes are not square for the sake of illustration.

Collisions. We identified in each trial the occurrence of a collision between the participant's car and either of the two surrounding cars. We identified the maneuvers during which collision occurred (i.e., overtaking, following, or bailing out) and the type of collisions (i.e., collision with the lead car or with the obstacle car). The frequency of collision was calculated for each participant and for each of the 14 MSV^{start} conditions. (A frequency of 100% indicates the occurrence of a collision on all five trials of a given MSV^{start} condition and 0% in none of them.)

TABLE 1

Initial Positions and Velocities of the Participant's, Lead, and Obstacle Cars Used to Compute the Minimum Satisfying Velocities MSV^{start} Conditions and Corresponding Values of the MSV^{start}/V_{max} Ratios Obtained When Manipulating V_{max} as a Between-Participants Variable

All cars	MSV^{start}	2.50	5	7.50	10	12.50	15	17.50	20	22.50	25	27.50	30	32.50	35
	V_L	1.25	2.5	3.75	5	6.25	7.5	8.75	10	11.25	12.5	13.75	15	16.25	17.5
	Y_L	102.21	102.21	102.21	102.21	102.21	102.21	102.21	102.21	102.21	102.21	102.21	102.21	102.21	102.21
	Y_0	243.79	243.79	243.79	243.79	243.79	243.79	243.79	243.79	243.79	243.79	243.79	243.79	243.79	243.79
Slow ($V_{max} = 25$ m/s)	MSV^{start}/V_{max}	10	20	30	40	50	60	70	80	90	100	110	120	130	140
Fast ($V_{max} = 32.5$ m/s)	MSV^{start}/V_{max}	7.69	15.39	23.08	30.77	38.46	46.15	53.85	61.54	69.23	76.92	84.62	92.31	100.00	107.69

Note. The 14 MSV^{start} conditions were set by adjusting the lead car's velocity (V_L) while keeping constant the positions on the y-axis of the lead (Y_L) and the obstacle (Y_0) cars relative to those of the participant's car.

Selection of action. We identified in each trial the maneuver selected by each participant: overtaking, bailing out, and following. The occurrence of an overtaking maneuver was defined as the succession of the five phases described earlier in the trajectory of the participant's car. The computation of overtaking frequency also included trials in which participants attempted an overtaking maneuver but collided with the obstacle car provided that the collision occurred after an initiation of a lateral excursion from the left to the right lanes. The occurrence of a bail-out maneuver was defined by the following four consecutive phases: (a) a lateral excursion from the right to the left lane, (b) driving in the left lane without passing the lead car, (c) a lateral excursion from the left to the right lane, and (d) passing the obstacle car while driving in the right lane behind the lead car. The computation for bailing out frequency also included trials in which participants collided with the obstacle car or the lead car provided that the collision occurred after the initiation of a lateral excursion from the left to the right lanes. The occurrence of a following maneuver was defined by (a) the absence of any lateral excursion from the lane during the whole trial and (b) passing the obstacle car while driving in the right lane after the lead car. The frequency of each maneuver was calculated for each participant and each of the 14 MSV^{start} conditions.

Regulation of action. Although our focus was on the decision to overtake or follow the lead vehicle, we also analyzed participants' behavior during the overtaking maneuver. For all trials during which participants attempted to perform an overtaking maneuver (including safe overtaking, safe bailing out, and maneuvers with collisions), we computed the ratio between the current velocity and the maximum velocity of the participant's car (V_S/V_{max}), and the ratio between the current MSV and the maximum velocity of the participant's car (MSV/V_{max}). Measurements were taken at the beginning of each of the five phases of overtaking maneuvers. Values were then averaged across trials for each participant and each of the 14 MSV^{start} conditions.

Statistical Analyses

The data from trials in which a car overtook the participant's car at the beginning of the trial were excluded from all analyses. A two-way, mixed-design ANOVA was performed on the frequency of overtaking with the independent variables being V_{max} (slow, fast) and MSV^{start} (14 MSV^{start} from 2.5 to 35 m/s by 2.5 m/s increments). The frequency of overtaking data were then fitted (using a least square procedure) by individually adjusting α and β in the logistic function provided by the equation $p(x) = 1/\left(1 + \left(\frac{x}{\alpha}\right)^{\beta}\right)$ in which $p(x)$ corresponds to the probability of observing an overtaking maneuver, and x is either MSV^{start} or

MSV^{start}/V_{max}. The resulting logistic fits were then used to derive the point of subjective equality (*PSE*; i.e., the critical value at which the overtaking frequency was equal to 50%) for each participant. *t* tests for independent groups were then performed on individual *PSE* values expressed as a function of MSV^{start} to quantify between group differences in the selection of overtaking maneuvers. In addition, *t* tests were performed on individual *PSE* values expressed as a function of MSV^{start}/V_{max} to test the prediction that behavior would be similar across groups when *MSV* was expressed as a ratio of V_{max}.

For all statistical analyses, the *p* value for statistical differences was set to .05. Partial effect sizes were computed (η_p^2) and post hoc comparisons were conducted using Newman-Keuls a posteriori tests.

PREDICTIONS

This study was designed to test the hypothesis that drivers are capable of perceiving *overtake-ability*, which allows them to perceive the requirements for overtaking in relation to their car's speed capabilities. Two predictions about participants' behavior in the context of the experiment can be derived from this hypothesis.

First, collisions should rarely occur when $MSV/V_{max} > 1$ because participants should perceive that overtaking is not within their capabilities and choose to follow the lead car rather than overtake. Second, the frequency of overtaking should decrease as MSV^{start} increases from zero to V_{max} for participants in both groups. Because V_{max} differs across groups, participants in the fast group should be more likely to overtake the lead vehicle for any given value of MSV^{start} (except for values at the low and high ends of the range, where overtaking frequency should be close to 100% and 0% for both groups). However, when MSV^{start} is expressed as a percentage of V_{max}, the frequency of overtaking should be similar across groups.

RESULTS

Collisions

The first set of analyses focused on the influence of MSV^{start} and V_{max} on the frequency of collisions. The black and gray histograms plotted on the lower and upper x-axis of the top panels of the Figure 4 show the mean percentage of collisions plotted as a function of MSV^{start} for the slow and fast cars, respectively. Collisions were infrequent, never exceeding 10% in any condition, indicating that participants drove safely in the large majority of trials. In addition, collisions occurred more often during overtaking and following maneuvers

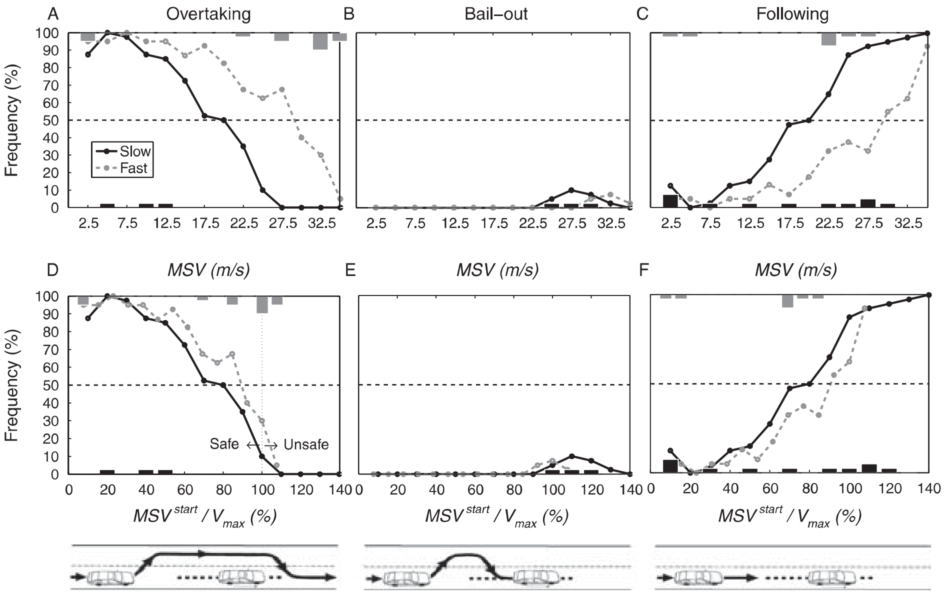

FIGURE 4 Average frequency of overtaking (A-B), bailing out (C-D), and following maneuvers (E-F) plotted as a function of MSV^{start} (top) and as a function of MSV^{start}/V_{max} (bottom) for the slow (plain black line) and fast cars (dotted gray line). The black histogram plotted on lower x-axis and the gray histogram plotted on the upper x-axis depict the average frequency of collisions in each maneuver (i.e., overtaking, bailing out, following) as a function of the MSV^{start} (top) and MSV^{start}/V_{max} (bottom) for the slow and fast cars, respectively.

(1.35% and 1.79%; left and right panels, respectively) than during bail-out maneuvers (0.27%; middle panel).

In order to determine whether collisions were most likely to occur when overtaking was not possible, we plotted histograms in the bottom panels of Figure 4 showing the same mean percentage of collisions as a function of the MSV^{start}/V_{max} ratio. Interestingly, collisions were most likely to occur when overtaking was possible (i.e., when $MSV^{start}/V_{max} \leq 1$), irrespective of both V_{max} (slow vs. fast) and whether the participant was overtaking, bailing out, or following. This is an interesting result because if collisions during overtaking were due to a failure to perceive the requirements for overtaking in relation to the car's speed capabilities, then one would expect most collisions to occur because drivers attempt to overtake when it is not within their capabilities to do so. The fact that collisions were most frequent when $MSV^{start}/V_{max} \leq 100\%$ suggests that failures during overtaking are due to factors other than the misperception of an affordance. Finally, the analysis of collisions also showed that collisions occurred more frequently with the lead car than with the obstacle car (2.15% vs. 0.72 %). Collisions with the lead car occurred because participants occasionally waited too long to initiate a change to the left lane, which resulted in rear-ending the lead car, or initiated a change back to the right lane too soon, resulting in sideswiping the lead car. Such collisions could reflect some difficulty in coordinating the movement of one's car with another moving car due to the unconventional operation of the steering wheel in our experiment. However, it is important to keep in mind that collisions with both the lead car and the obstacle car were quite infrequent.

Selection of Action

The next set of analyses focused on the influence of MSV^{start} and V_{max} on the frequency of overtaking. The black and gray curves in Figure 4A show the mean frequency of overtaking plotted as a function of MSV^{start} for the slow and fast cars, respectively. As expected, overtaking frequency decreased as MSV^{start} increased roughly according to a sigmoid function from 100% to 0% for each participant. In addition, although participants in the slow car group were less likely to attempt an overtaking maneuver, the relation between overtaking frequency and MSV^{start} followed a similar shape for the two groups.

A two-way ($MSV^{start} \times V_{max}$) ANOVA with repeated measures on MSV^{start} performed on overtaking frequency revealed a main effect of MSV^{start} ($F[13, 182] = 37.25$, $p < .05$, $\eta_p^2 = .73$). The ANOVA also revealed a main effect of V_{max} ($F[1, 14] = 13.73$, $p < .05$, $\eta_p^2 = .49$), confirming that participants in the slow car group attempted significantly fewer overtaking maneuvers than participants in the fast car group (46.78% vs. 70.84%). The overtaking frequency data from the two groups were thus fitted with a logistic function to compute the *PSE* values expressed as a function of MSV^{start} conditions (cf. Table 2). A *t* test for independent groups performed on *PSE* values revealed that the *PSE* is significantly inferior for the slow car group ($M = 18.64$ m/s) compared with the fast car group ($M = 27.33$ m/s; $t = -3.38$, $df = 14$, $p < .05$), confirming that participants in the slow car and fast car groups exhibited different overtaking frequencies for the same MSV^{start} conditions.

The black and gray curves in Figure 4D depict mean frequency of overtaking as a function of MSV^{start}/V_{max} for the slow and fast cars, respectively. It is important to note that overtaking frequency dropped to 0% for both groups very close to the point at which MSV^{start}/V_{max} exceeded 100% (i.e., when the *MSV* to successfully overtake the lead car was greater than the car's maximum velocity). This suggests that participants in both groups were able to reliably perceive when overtaking was not within the capabilities of their car. The curves for the two groups in Figure 4D nearly overlap, suggesting that the likelihood of overtaking was similar across groups for most values of MSV^{start} expressed as a ratio of V_{max}. Again, the overtaking frequency data for each individual participant in both groups were fitted with a logistic function to compute the *PSE* values expressed

TABLE 2

Individual Values of Point of Subjective Equality (*PSE*) Provided by the Best Logistic Fits of Individual Mean Frequency of Overtaking Expressed as a Function of MSV^{start} Values and as a Function of MSV^{start}/V_{max} Values for the Slow and Fast Groups

Group	*Participant's ID Number*	α	*B*	R^2	MSV^{start} *PSE* (m/s)	$MSV^{start}/V_{\max}$ *PSE* (%)
Slow	1	77.68	6.47	0.92	19.42	77.68
Slow	3	49.50	4.09	0.90	12.34	49.37
Slow	7	57.99	9.39	0.98	14.62	58.49
Slow	10	82.00	10.75	0.93	20.50	82.00
Slow	12	100.33	123.10	0.93	25.08	100.33
Slow	14	82.04	55.06	0.99	20.53	82.11
Slow	16	64.90	4.19	0.95	16.23	64.90
Slow	18	81.53	5.23	0.83	20.38	81.53
Mean ± Std		74.50 ± 16.17	27.28 ± 42.32	0.93 ± 0.05	18.64 ± 4.03	74.55 ± 16.13
Fast	2	71.97	7.09	0.91	23.39	71.97
Fast	4	86.26	71.67	0.97	28.04	86.26
Fast	6	101.15	19.17	0.89	32.87	101.15
Fast	8	57.92	6.79	0.95	18.83	57.92
Fast	9	97.04	8.50	0.86	31.32	96.37
Fast	11	58.78	2.74	0.88	19.10	58.78
Fast	13	99.10	153.89	0.97	32.21	99.10
Fast	15	99.74	4.88	0.50	32.89	101.21
Mean ± Std		83.99 ± 18.54	34.34 ± 53.39	0.87 ± 0.15	27.33 ± 6.06	84.09 ± 18.66

Note. The R^2, α, and β values provided by each individual logistic fit are also provided.

as a function MSV^{start}/V_{max}. The *t* test for independent groups performed on *PSE* values reveals that *PSE* is not significantly different between the slow car and fast car groups ($M = 79.32$, $t = -1.09$, $df = 14$, $p > .05$).

Although the *PSE* values were not significantly different, there does appear to be a trend toward a higher percentage of overtaking for participants in the fast condition. We can only speculate about why this trend exists. One possibility is that on trials in which there was uncertainty about whether to overtake or follow, participants in the fast group were more biased to overtake compared with participants in the slow group for the following reason. The overall percentage of trials in which overtaking was possible was greater for participants in the fast group. This is because the set of MSV^{start} values were the same for the two groups, but participants in the fast group could accelerate to a faster V_{max}. This may have induced a bias among participants in the fast group to overtake rather than follow, which could account for the small differences between the two groups in Figures 4D and 4F.

Taken together, the analysis of overtaking frequency is consistent with the hypothesis that the decision about whether to overtake was based on the perception of the overtaking affordance, defined by the ratio of *MSV* to V_{max}. When safe overtaking was not possible (i.e., when $MSV^{start}/V_{max} > 1$), drivers consistently chose to follow the lead vehicle rather than attempt an overtaking maneuver (see Figure 4C and 4F). Close inspection of Figure 4C and 4F reveals that whereas overtaking frequencies were equal to zero when the MSV^{start}/V_{max} ratio exceeded 100%, following frequencies did not reach 100% at the same point. This was due to 4 participants of the fast group and 3 participants of the slow group who occasionally executed bail-out maneuvers when the MSV^{start}/V_{max} ratio was close to 100% (see Figure 4B and 4E).

Regulation of Action

Having established the role of MSV^{start}/V_{max} in the selection of driving maneuvers, we now consider the regulation of velocity during overtaking. The small vignettes of the lower panel of the Figure 5 depict the unfolding of the current *MSV* and velocity of the participant (V_S) over time for a representative participant over the five repetitions of each of the MSV^{start}/V_{max} conditions.

When MSV^{start}/V_{max} was low at the start of the trial (i.e., less than 40%; the first five vignettes in the lower panel of Figure 5; see also the A vignette in the upper panel of Figure 5 for a typical labeled trial), participants consistently increased the car's velocity throughout the trial up to V_{max}. The consistent increase in velocity from the beginning of the trial makes sense as the low initial value of MSV^{start}/V_{max} specifies that overtaking is easily within the car's velocity capabilities.

Participants' behavior was also quite consistent across trials when MSV^{start}/V_{max} was high at the start of the trial (i.e., greater than 75%; the last five vignettes

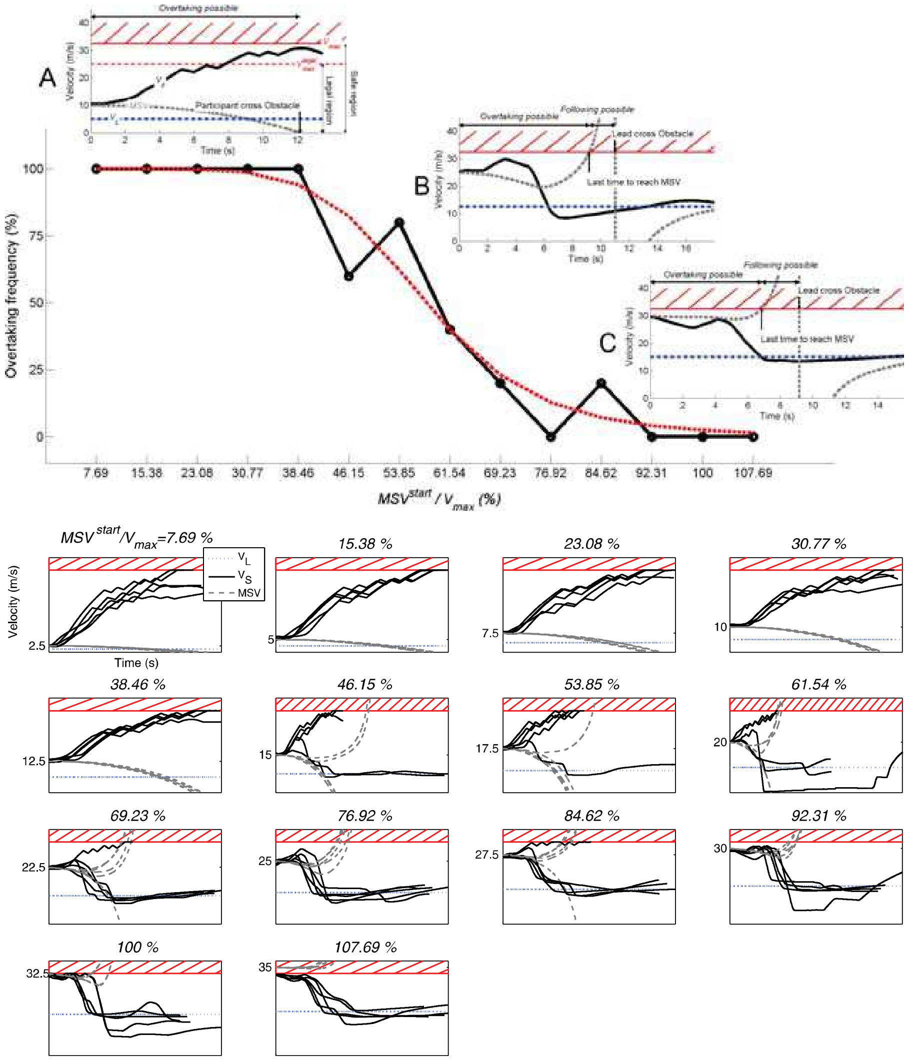

FIGURE 5 Typical individual set of overtaking frequencies monitored with participant ID number 8 over the five repetitions of each condition. In the upper panel, the sigmoid curve (dotted line) depicts the individual fit of overtaking frequencies by a logistic function, plotted as a function of the MSV^{start}/V_{max} ratios with the point of subjective equality. The A-C large vignettes depict trial's samples of kinematics monitored during low, medium, and high MSV^{start}/V_{max} conditions (30%, 75%, and 90%) and giving rise to overtaking, bailing out, and following maneuvers, respectively. Vertical arrows indicate punctual temporal events (e.g., the time at which the participant or the lead car crosses the level of the obstacle car). Horizontal arrows indicate the possible action modes (e.g., overtaking and following maneuvers). In the lower panel, the 14 small vignettes depict the current participant's velocity (V_S; solid black line), lead car's velocity (V_L; dotted blue line), minimum satisfying velocity for overtaking (MSV; dotted gray line), maximum velocity of the participant's car (V_{max}; hatched red area) monitored during the five repetitions of each MSV^{start}/V_{max} ratio.

in the lower panel of Figure 5; see also the C vignette in the upper panel of Figure 5). In these conditions, the *MSV* at the beginning of the trial ranged from slightly less than V_{max} to slightly greater than V_{max} (horizontal red line), which means that the margin for safe overtaking was very small or nonexistent. Given the instructions to avoid collisions as one would do in the real world, it is not surprising that participants consistently decelerated until their speed fell below that of the lead car and followed, rather than overtook, the lead car.

Behavior was somewhat less consistent for values of MSV^{start}/V_{max} in the middle of the range as depicted in the vignettes corresponding to values of MSV^{start}/V_{max} between 40% and 75% in the lower panel of Figure 5. Participants accelerated to V_{max} on some trials and decelerated to match the speed of the lead car on other trials. Occasionally, participants started to accelerate and initiated an overtaking maneuver by switching to the left lane but then decelerated to the speed of the lead car and returned to the right lane to follow the lead car. The B vignette in the upper panel of Figure 5 shows an example of such a trial, which we classified as a bailout.

We also analyzed the mean ratio of the participant's car velocity (V_S) to V_{max} at the beginning of each of the five phases of the overtaking maneuver (see Figure 6). V_S/V_{max} is plotted as a function of MSV^{start}/V_{max} for both successful (safe) and unsuccessful (unsafe) trials. In accordance with the experimental protocol, $V_S/V_{\max}$ varied systematically with MSV^{start}/V_{max} at the beginning of each trial (Start phase). Over successive phases, V_S/V_{max} approached 100%, indicating that participants generally accelerated to V_{max} throughout the trial when they overtook the lead car. Interestingly, participants' mean speed on unsafe trials (designated by the star symbols in Figure 6) was consistently greater than their mean speed on safe trials (designated by the circular symbols) at the beginning of the Left phase. This suggests that one of the causes of collisions was driving too fast during the Start phase, which elevated the risk of rear-ending the lead car before completing the lane change. Likewise, participants' mean speed on unsafe trials was consistently less than their mean speed on safe trials during the Pass, Right, and End phases. Thus, another cause of collisions was driving too slow after switching into the left lane, which may have occurred when participants attempted to bail out too late. These analyses provide some insight into the causes of collisions. However, it is important to keep in mind that collisions were very infrequent and almost never resulted from attempting to overtake the lead vehicle when overtaking was not possible.

DISCUSSION

The objective of this study was to investigate the perceptual-motor processes underlying visually guided overtaking maneuvers. We hypothesized that

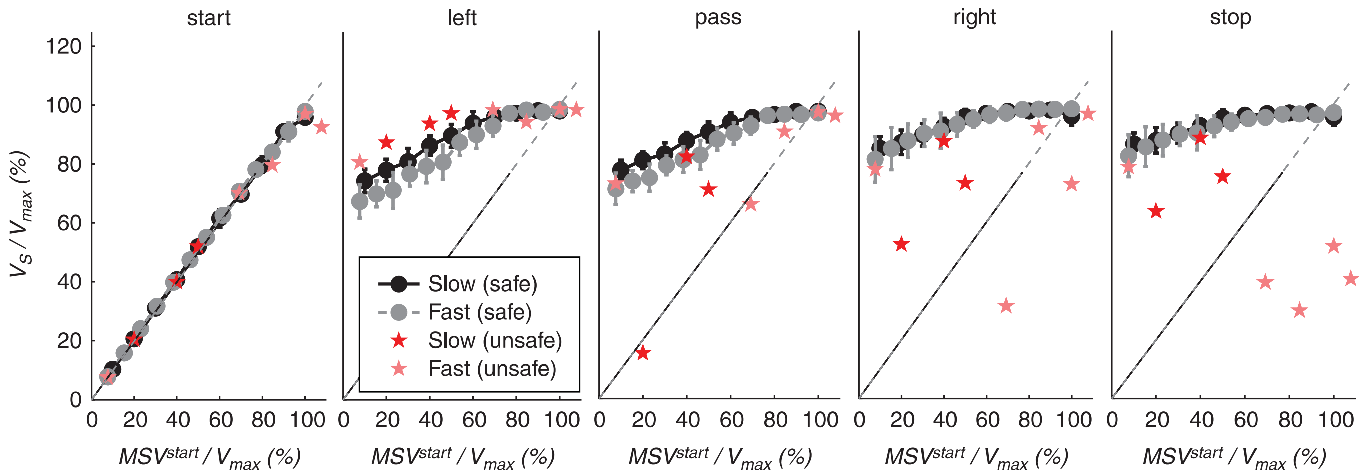

FIGURE 6 Average ratio between the participant's velocity over the participant's maximum velocity (V_S/V_{max}) plotted as a function of the MSV^{start}/V_{max} conditions during the five successive phases of the overtaking maneuver. Values are computed during safe (• symbols) and unsafe overtaking maneuvers (★symbols) with dark and light colors for the slow and fast cars, respectively. Vertical bars depict the standard deviation of individual mean.

drivers deciding whether or not to initiate an overtake of a lead car would rely on an *overtake-ability* affordance, which we defined as the ratio of the velocity needed to overtake the lead car while avoiding a collision with the obstacle car (i.e., the minimum satisfying velocity, or *MSV*) to the maximum velocity of the driver's car (V_{max}). In a virtual environment, two groups of experienced drivers drove either a slow or a fast virtual car and performed overtaking maneuvers, if deemed possible, as safely as in real-world situations. By varying V_{max} as a between-participants factor and MSV^{start} as a within-participants factor, we manipulated *overtake-ability* in 14 conditions ranging from easily overtake-able when $MSV^{start}/V_{max} < 100\%$ to not overtake-able when $MSV^{start}/V_{max} > 100\%$.

Analyses of Collisions

We hypothesized that if overtaking decisions are based on the perception of *overtake-ability*, then drivers should be able to reliably distinguish between situations in which overtaking is within their car's capabilities and situations in which overtaking is not within their car's capabilities. As such, collisions should be infrequent when the velocity needed to overtake is greater than the car's maximum velocity (i.e., $MSV^{start}/V_{max} > 100\%$) because drivers should perceive that overtaking is not possible and should choose to follow the lead vehicle rather than overtake. The findings were consistent with this prediction. Collisions were infrequent and when they did occur, they were no more likely to occur on trials in which overtaking was not possible compared with trials in which overtaking was possible.

The frequency of collisions in our study (overall, 2.95% trials) was well below the frequency of collisions (approximately 15% of trials) reported in other laboratory studies (Gordon & Mast, 1970; Gray & Regan, 2005). This discrepancy could be due to the fact that the obstacle car was stationary in the present experiment and approaching in the other studies. This leads to a possible alternative explanation for collisions during overtaking. Rather than collisions resulting from a failure to be properly attuned to the capabilities of one's car, collisions may occur because drivers misperceive the approach speed or time to contact of the other car (Björkman, 1963; Silver & Farber, 1967). This seems like a plausible hypothesis given how far away the other car typically is when the driver has to make the decision about whether or not to overtake.

Driver's Sensitivity to the MSV^{start}/V_{max} Ratio for Selecting Overtaking Action

We also investigated the relationship between the selection of a driving maneuver (i.e., overtaking, bailing out, following) and the possibility to perform an overtaking maneuver (i.e., *overtake-ability*). These analyses revealed that the frequency of overtaking dropped from 100% to 0% and the frequency of following rose from 0% to 100% as MSV^{start} approached V_{max}. Bail-outs were infrequent. Furthermore, although participants in the fast car group were more likely to overtake than participants in the slow car group, their behavior was similar when overtaking and following frequencies were plotted as a function of the MSV^{start}/V_{max} ratio. These analyses, when taken together with the finding that collisions were infrequent, provide further evidence that drivers are sensitive to the velocity capabilities of their cars and that they are able to scale overtaking requirements to their capabilities when choosing whether to overtake. The findings also support the hypothesis that the selection of overtaking actions is driven by the perception of affordances.

It is interesting to note that overtaking frequency is not strictly equal to 0% when MSV^{start}/V_{max} is equal to 100% as one might expect but rather 10% and 29.9% for the slow and fast cars, respectively (see Figure 4D). This could reflect a minor difference between the *MSV* that we calculated for the purposes of our analyses and the *MSV* that participants actually perceived. When we calculated *MSV* for our analyses, we assumed that the participant's car must completely return to the right lane before it reaches the obstacle car. However, because all three cars were slightly narrower than the lane, it is possible for the participant's car to pass by the obstacle car without a collision before completely returning to the right lane. Obviously, this would be an extremely risky maneuver. However, if participants perceived *MSV* in a way that allows for this riskier maneuver, they may have perceived that overtaking was possible even when MSV^{start}/V_{max} (computed in the nonrisky way) was equal to 100%.

Additional Issues

Finally, we consider two theoretically significant issues that were not directly addressed by this study but that could be considered in future studies of overtaking from an affordance-based perspective.

First, V_{max} is not the only property of the car that affects *overtake-ability*. The car's maximum turning rate also determines whether overtaking is possible because the faster the driver can change lanes, the more time he or she has to overtake the lead vehicle before having to return to the right lane. Similarly, *overtake-ability* is also determined by the dimensions of the car (i.e., longer and wider cars require faster maximum satisfying velocities). We cannot draw any conclusions about drivers' attunement to the dimensions of their cars on the basis of this study. However, previous studies have demonstrated that humans are capable of perceiving affordances in other contexts when the dimensions of their bodies are altered by handheld objects and tools (Ishak, Adolph, & Lin, 2008; Wagman & Malek, 2007; Wagman & Taylor, 2005).

Second, although we focused on the perception of *overtake-ability*, overtaking may also involve the simultaneous perception of another affordance. Even after a driver initiates an overtaking maneuver by switching to the left lane and accelerating, it may still be possible to decelerate and return to the right lane behind the lead car. We referred to such maneuvers as bailouts and observed them on a small percentage of trials, presumably when the participant initiated an overtaking maneuver and later realized that the margin for error was too small. However, in order to bail out, the driver must be able to decelerate rapidly enough to return to the left lane behind the lead car before arriving at the obstacle car. If the driver waits too long and the car's deceleration capabilities are too weak, then bailing out may not be possible. In other words, in addition to perceiving *overtake-ability*, the driver may also need to perceive whether bailing out is still within his or her capabilities. In this regard, a more complete account of drivers' behavior during overtaking may be possible by considering overtaking in terms of a competition between two affordances (Marti, Morice, & Montagne, 2014).

Conclusions

In conclusion, the findings of this study show that drivers are sensitive to the limits of their car's velocity capabilities and properly scale the overtaking requirements with reference to these limits when selecting and regulating overtaking, as suggested by the affordance-based framework. Collisions that occur during overtaking may be due to factors other than a failure to properly take the speed capabilities of one's car into account, such as a misperception of the approach speed or time to contact of the car in the overtaking lane.

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