Influence respective des *affordances MSV sur Vmax* et *MSA sur Amax* sur la prise de décision

III.2.1 Résumé de l'expérimentation 2

Introduction

Dans cette expérience, nous questionnerons la sensibilité du conducteur à des propriétés cinématiques telles que la vitesse et l'accélération maximale du véhicule conduit. Notre étude précédente (Morice et al., 2015) a démontré que les conducteurs réalisaient leur dépassement en fonction du ratio entre une propriété du système agent-environnement (i.e., la Vitesse Minimale Satisfaisante pour réussir le dépassement, *MSV*) et une propriété de l'agent (i.e., Vitesse maximale du véhicule conduit, *Vmax*). L'*affordance* de dépassement *MSV/Vmax* a ainsi été formalisée à partir de propriétés définies dans une unité de vitesse (m/s). Toutefois, dans la vie réelle les véhicules ne sont pas seulement bornés par une vitesse maximale mais également par une accélération maximale qui contraint la performance des conducteurs. Une telle limite d'action est, par exemple, essentielle dans la perception des possibilités de traverser une intersection en toute sécurité (Marti et al., 2015). Les possibilités de dépasser seraient contraintes à la fois par une vitesse maximale et une accélération maximale. Les conducteurs pourraient alors améliorer leur perception des possibilités de dépasser en s'appuyant non seulement sur la vitesse maximale mais également sur leur accélération maximale. En ce sens, nous postulons que la définition de l'*affordance* de dépassement peut être étendue au ratio entre l'accélération minimale satisfaisante pour réussir le dépassement (*MSA*) et l'accélération maximale du véhicule conduit (*Amax*). Cette nouvelle formalisation devrait ainsi enrichir la précédente en renseignant plus précisément les conducteurs sur leurs possibilités de dépasser.

Méthode

Afin de tester l'hypothèse selon laquelle les conducteurs percevraient préférentiellement une *affordance* de dépassement automobile formalisée à partir de propriétés d'intérêts définies dans une unité d'accélération, nous avons constitué deux groupes de dix conducteurs chacun. Le premier groupe possède une accélération maximale faible (*Amax* = 2 m/s²) et le second groupe dispose, quant à lui, d'une accélération maximale élevée (*Amax* = 3.5 m/s²). Dans chacune des conditions expérimentales soumises aux conducteurs, la difficulté du dépassement est dépendante à la fois des cinq valeurs de *MSV* calculées à partir de la vitesse maximale des participants (*Vmax* = 35 m/s) et des quatre valeurs de *MSA* calculées à partir des accélérations maximales des participants. De plus, dans chaque essai, les conducteurs possédaient une vitesse initiale inférieure à la *MSV* initiale afin de permettre l'utilisation éventuelle de la *MSA*.

De ce fait, pour chaque condition de *MSV* et de *MSA*, les participants du groupe avec une accélération maximale élevée (*Amax* = 3.5 m/s²) devraient dépasser davantage que les participants du groupe avec une accélération maximale faible (*Amax* = 2 m/s). Par ailleurs, la manipulation des difficultés de dépassements liées à la *MSV* devrait avoir moins d'incidence sur le comportement de dépassement que la manipulation des difficultés de dépassement liées à la *MSA.*

Résultats

À l'aide d'une régression factorielle des courbes individuelles des fréquences de dépassement, nous avons mis en évidence une variation des fréquences de dépassement selon les capacités d'accélération maximales des véhicules conduits. Cette différence comportementale entre les groupes se produit lorsque les courbes psychométriques sont exprimées dans une échelle de mesure extrinsèque (i.e., en fonction de *MSV* et de *MSA*). En d'autres termes, le groupe de conducteurs avec une accélération maximale élevée (*Amax* = 3.5 m/s²) double plus fréquemment que le groupe de conducteurs possédant une accélération maximale faible (*Amax* = 2 m/s²). À l'inverse, lorsque les fréquences de dépassement sont exprimées dans une échelle de mesure intrinsèque (i.e., en fonction des ratios *MSV/Vmax* et *MSA/Amax*), les analyses statistiques effectuées sur les coefficients de la régression factorielle ne permettent plus de conclure à l'existence de différences significatives entre les groupes de conducteurs.

Par ailleurs, une régression linéaire multiple est effectuée sur les moyennes individuelles des fréquences de dépassement en combinant *MSA/Amax* avec plusieurs prédicteurs possibles : *MSV/Vmax*, *Vs*, *(MSV-Vs)/Ts* et *Ts*, défini comme le temps pour atteindre la *MSV*. Nous avons ainsi pu quantifier le poids de chaque couple de prédicteurs dans le modèle de dépassement automobile à l'aide des R^2 ajustés. Conformément à notre hypothèse, l'*affordance MSA/Amax* est préférentiellement perçue par les conducteurs quels que soient les prédicteurs associés : en moyenne, 76.4% des fréquences de dépassement sont expliquées par la nouvelle *affordance* de dépassement *MSA/Amax.* Toutefois, de façon inattendue, le couple *MSA*/*Amax* et *Ts* explique significativement le comportement de dépassement, à l'instar du couple *MSA*/*Amax* et *MSV*/*Vmax*.

Discussion

Conformément à la théorie des *affordances* (J. J. Gibson, 1986) et à l'*affordance-based control* (Fajen, 2007a), les résultats comportementaux obtenus mettent en évidence la capacité des conducteurs automobiles à agir dans leur dépassement en considérant à la fois les capacités de vitesse maximales (i.e., *Vmax*) et d'accélération maximales (i.e., *Amax*) de leur véhicule. Toutefois, les résultats de la régression linéaire multiple mettent en évidence une utilisation préférentielle de l'*affordance* de dépassement (i.e., *MSA/Amax*), quels que soient les groupes de conducteurs. Cette utilisation préférentielle pourrait s'expliquer par un principe de sécurité (de Rugy, Montagne, Buekers, & Laurent, 2001) puisque la priorité est accordée à l'*affordance MSA/Amax* qui renseigne à la fois plus précisément et plus précocement le conducteur sur la faisabilité du dépassement. Dans l'intérêt du conducteur, il serait donc préférable de percevoir cette dernière. Par ailleurs, la sensibilité inattendue des conducteurs à la propriété *Ts*, traduite par son poids dans la régression du comportement de dépassement, pourrait s'expliquer par sa capacité à informer le conducteur des contraintes temporelles du dépassement et de ce fait de la possibilité d'accéder ou non à la *MSA* lorsque les contraintes temporelles sont sévères. En d'autres termes, la propriété temporelle *Ts* renseignerait le conducteur sur la marge de sécurité dont il dispose pour rejoindre *MSA* dans des conditions où le degré de liberté du conducteur est très faible, c'est-à-dire où *MSA* est très proche des limites d'action. Cette nouvelle propriété permettrait donc au conducteur de choisir un mode d'action pertinent. Lors de cette expérimentation, nous avons ainsi pu formaliser une nouvelle *affordance* de dépassement et confirmer la validité de la théorie des *affordances* (J. J. Gibson) ainsi que sa formalisation mathématique (Warren, 1984). Enfin, les résultats obtenus étendent ceux de Morice et al. (2015) en démontrant que les conducteurs sont non seulement sensibles à leur vitesse maximale mais également à leur accélération maximale pour percevoir les possibilités de dépasser, en accord avec le cadre théorique des *affordances* (Fajen, 2007a).

III.2.2 Manuscrit de l'expérimentation 2

High and low order overtaking-ability affordances: Drivers rely on the maximum velocity and acceleration of their cars to perform overtaking maneuvers

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Objective: Do drivers take into account the action boundaries of their car when overtaking?

Background: The Morice et al. (2015) affordance-based approach to visually guided overtaking suggests that the "overtake-ability" affordance can be formalized as the ratio of the "minimum satisfying velocity" (*MSV*) of the maneuver to the maximum velocity (V_{max}) of the driven car. This definition however, ignores the maximum acceleration of the vehicle. We hypothesize that drivers may be sensitive to an affordance redefined with the ratio of the "minimum satisfying acceleration" *(MSA)* to the maximum acceleration (A_{max}) of the car.

Method: Two groups of nine drivers drove car differing in their Amax. They were instructed to attempt overtaking maneuvers in 25 situations resulting from the combination of five *MSA* and five *MSV* values.

Results: When overtaking frequency was expressed as a function of *MSV* and *MSA*, maneuvers were found to be initiated differently for the two groups. However, when expressed as a function of MSV/V_{max} and MSA/A_{max}, overtaking frequency was quite similar for both groups. Finally, a multiple regression coefficient analysis demonstrated that overtaking decisions are fully explained by a composite variable comprising MSA/A_{max} and the time required to reach *MSV*.

Conclusion: Drivers reliably decide whether overtaking is safe (or not) by using low and high order variables taking into account their car's maximum velocity and acceleration respectively, as predicted by "affordance-based control" theory.

Application: Potential applications include the design of overtaking assistance, which should exploit the MSA/A_{max} variables in order to suggest perceptually relevant overtaking solutions.

Keywords: Driving; Overtaking; Affordance; Acceleration; Virtual reality

Précis: We study overtaking in a virtual reality situation from the perspective of affordance theory, and show that drivers perceive overtaking opportunities on a scale that takes into account their car's maximum velocity and acceleration.

INTRODUCTION

In France, failed overtaking maneuvers are responsible for 21.5% of fatal accidents ("National Interministerial Observatory for Road Safety," 2011). Similar, alarming observations have been made in other countries (DEKRA, 2013; Duivenvoorden, 2010). The large number of fatalities has motivated the launch of prevention plans (The United Kindgom Royal Society for the Prevention of Accidents, 2009), modifications to legislation (Williams & Preusser, 1997) or development of Advanced Driver Assistance Systems (Hegeman, Brookhuis, & Hoogendoorn, 2005; Hegeman, van der Horst, Brookhuis, & Hoogendoorn, 2007; Jamson, Chorlton, & Carsten, 2012; Milanes et al., 2012). However, for maximum efficiency, such preventive measures must be accompanied by a better understanding of the underlying human factors and the perceptual processes used by drivers to identify safe overtaking conditions. To this aim, we investigate whether drivers are sensitive to their vehicle's maximum velocity and acceleration while overtaking.

Affordance-based models (Fajen, 2005b, 2007a) provide a framework that makes drivers' sensitivity to the kinematic limits of their car crucial for the perception of overtaking situations. For example, the "shrinking gap" problem (Fajen & Matthis, 2011) shows that subjects attempting to pass safely through a moving gap rely on a variable that specifies (in intrinsic units) their minimum locomotor speed. This study led us to formalize the minimum speed necessary to safely overtake a lead car while avoiding oncoming traffic (Morice et al., 2015). In virtual reality, we manipulated independently the "minimum satisfying velocity" (*MSV*) allowing to safely overtake the lead car and the maximum velocity (V_{max}) of the driver's car. When $MSV/V_{max} \leq 1$, it was physically possible to overtake the lead car because the *MSV* was lower or equal to the maximum velocity of the driver's car (V_{max}); otherwise overtaking was not possible. We found that overtaking frequency decreased when the MSV/V_{max} ratio approached 1, and that overtaking frequency was not significantly affected by V_{max} provided that drivers' behavior was expressed as a function of the MSV/V_{max} ratio. Therefore, the MSV/V_{max} variable allows for perception of the safeness of overtaking maneuvers depending on the maximum velocity of the driven car. However, real life cars are not only bounded by a maximum velocity but also by a maximum acceleration that also constrains the performance envelope of a car as illustrated in Figure 27. Indeed, in combination to the maximum velocity (V_{max}), the maximum acceleration (A_{max})

determines the driver's field of possibilities (the "reachable states"). Such an action limit is for instance essential in the perception of crossing possibility while approaching an intersection (Marti, Morice, & Montagne, 2015; McKenna, 2004).

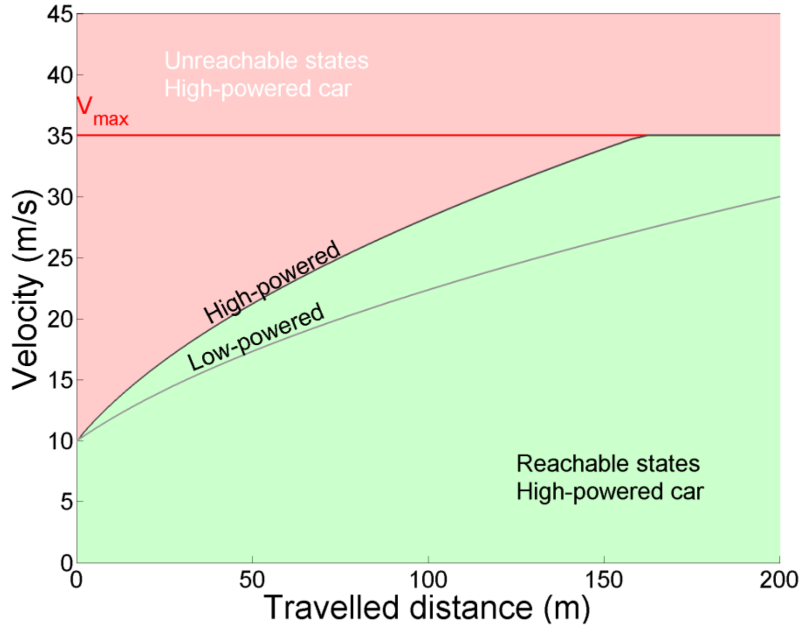

Figure 27. Numerical simulations of the performance state space for two accelerating cars as a function of maximal acceleration (A_{max} = 2 and 3.5 m/s² for *Low-Powered* and *High-Powered* cars, respectively) and maximal velocity (V_{max} = 35 m/s). The colored spaces partition the state space in terms of reachable and unreachable states for the high-powered car.

Both maximum velocity and maximum acceleration would therefore limit driver's overtaking possibilities. Indeed, as demonstrated by Morice et al. (2015), a larger V_{max} would offer drivers more opportunities to perform a safe overtaking maneuver. This last comment is illustrated in the upper row of Figure 28, showing numerical simulations of two cars constrained by different V_{max} (i.e., *Slow* and *Fast* cars), attempting to overtake a lead car moving at a constant velocity while avoiding to collide a stationary obstacle standing on the opposite lane. The panel B shows that *Slow* and *Fast* cars accelerate similarly from an initial velocity of 10 m/s to reach a higher *MSV*. When reaching its V_{max}, the *Slow* car stops accelerating and moves at a constant velocity, preventing it to catch *MSV*. This moment corresponds in panel A to the point from which *Slow* and *Fast* cars' trajectories diverge. From this moment onwards, the *Slow* car's trajectory is no more able to pass the lead car before reaching the stationary obstacle position.

Conversely, the *Fast* car benefits from more time to continue accelerating and reach *MSV* before exceeding V_{max}. This allows it to safely overtake the lead car. We hypothesize that, in parallel, the driver of a high-powered car would also benefit from a larger maximum acceleration as illustrated in the lower row of Figure 28. Indeed, if one considers the same initial velocity of 10 m/s, the larger the maximum acceleration (i.e., *high-powered* vs. *low-powered* car) the safer overtaking would be, regardless V_{max}, as *MSV* will be reached quicker (panel D). Hence, the car's maximum acceleration, in addition to the car's maximum velocity, determines drivers' overtaking opportunities.

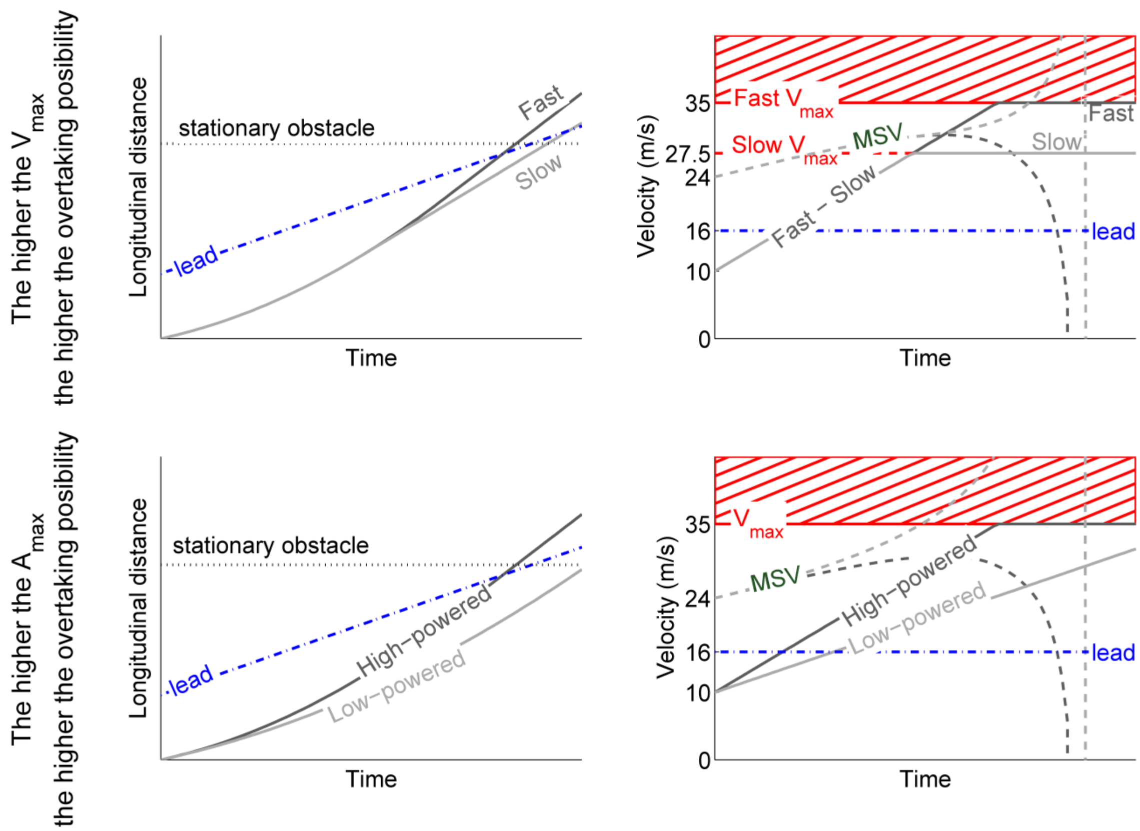

Figure 28. Position (left panels) and velocity (right panels) time-series for cars limited by different maximum velocity (*Vmax* = 27.5 and 35 m/s for *Slow* and *Fast* cars, respectively; upper row) and acceleration (*Amax* = 2 and 3.5 m/s² for *Low-Powered* and *High-Powered* cars, respectively; lower row). *Fast* and *High-Powered* cars offer safer overtaking possibilities than *Slow* and *Low-Powered* vehicles.

Drivers would take advantage from relying on maximum acceleration in addition to maximum velocity to improve their perception of overtaking possibility. We therefore hypothesize that the definition of the *overtake-ability* affordance should be extended by scaling the minimum satisfying acceleration (*MSA*), required to accelerate from the current velocity to the minimum satisfying velocity (*MSV*) before it exceeds the maximum velocity of the car (V_{max}), by the maximum acceleration of the vehicle being driven (A_{max}). The MSA/A_{max} ratio would thus be an enriched property with regards to MSV/V_{max}, reflecting better the car's action possibility.

Experiment

This experiment investigated overtaking in an affordance-based framework. Using a virtual reality scenario, we tested the hypothesis that drivers perceive overtaking affordances by perceiving the MSA/A_{max} ratio.

If drivers are sensitive to V_{max} only, they are expected to overtake in any situation where $MSV/V_{max} \leq 1$, whatever the MSA/A_{max} ratio. If drivers are sensitive to A_{max}, they will decide to overtake only in situations where $MSA/A_{max} \leq 1$ (including conditions where $MSV/V_{max} \leq 1$).

METHOD

Participants

Eighteen volunteers (13 men and 5 women) were divided into two mixed-gender groups. Their average age was 22.84 years (SD = 2.63 years) and all had normal or corrected-to-normal vision. All participants held a valid driving license and had an average of 3.58 years' driving experience (SD = 2.24 years). The experimental protocol was approved by the local ethics committee. Participants were not told the purpose of the study.

Task

Drivers were asked to perform overtaking maneuvers, if deemed possible. They were free to accelerate or brake by using appropriate pedals. They controlled the initiation of lateral excursions between lanes (an overtaking maneuver) by turning the steering wheel over ± 30°: a counterclockwise turn moved the car from the right to the left lane, whereas a clockwise turn moved the car in the opposite direction. Feedback about the speed of the vehicle was provided by optic flow and engine noise; speedometer was not displayed.

Apparatus

Figure 29 illustrates the fixed-base driving simulator. Participants sat in a playseat (Mobsim, France); they manipulated two pedals (Trackstar 6000 GTS) with their right foot, and used their hands to turn a steering wheel (ECCI, Trackstar 6000 GTS). The data from the pedals and steering wheel were sent to a computer, and OpenGL-based software controlled the motion of the virtual car on-line. From the driver's viewpoint, the virtual scene was rendered as two 800 × 600 pixels stereoscopic images refreshed at 75 Hz in a head-mounted display (Hi-res 900 stereo, Cybermind Corp). An electromagnetic tracking system (Flock of Birds, Ascension Technology Corp.) was used to enslave the virtual scene to driver's head rotations from a fixed observation point (0.975 m above ground level, at the center of the driver's playseat). The driver could display side or/and center rear-view mirrors in the virtual scene by holding dedicated buttons. Mirrors were sized and located realistically relative to the virtual car so as to allow drivers, if deemed comfortable, to fixate the visual content of mirrors while controlling the surrounding driving environment in peripheral vision.

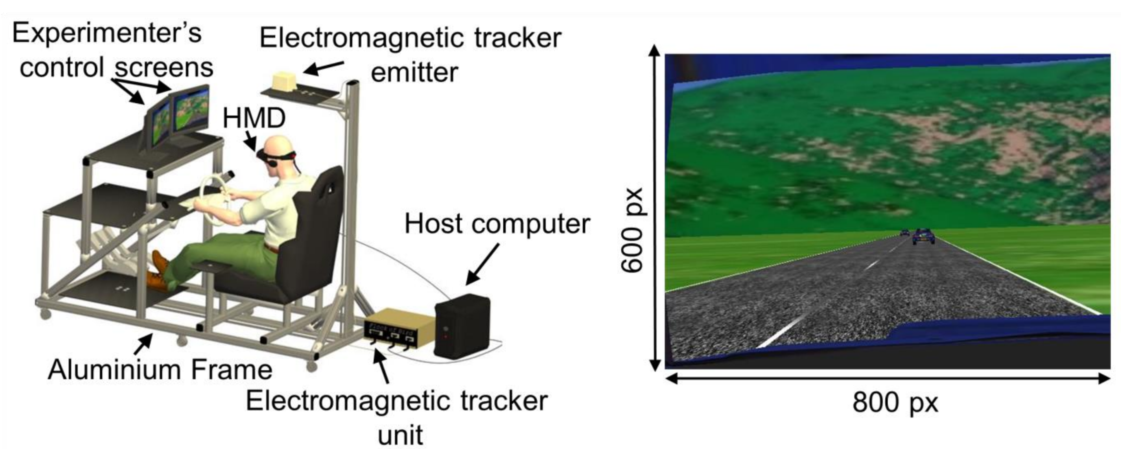

Figure 29. (Left) Overview of the virtual reality set-up. Participants wearing a head-mounted display sat on a playseat. (Right) Typical screenshot of the virtual scene prior to an overtaking maneuver, including two 3.5 m wide lanes, two 4.415 m long × 1.740 m wide × 1.475 m high cars, respectively acting as an obstacle and a lead car, and the landscape. At the trial start, obstacle and lead cars optical diagonal sizes were equal to 0.57 and 1.77°, respectively.

Procedure

Participants initially performed 20 practice trials to familiarize themselves with the task. Each trial began with an initial phase during which the virtual car was moved by the computer at a velocity V_s (see next subsection and Table 3) and a 0 m/s² acceleration until it crosses the starting line. From this point, a lead and a stationary obstacle vehicle appeared on the right and left lane respectively, and drivers were free to control their acceleration and position using the pedals and steering wheel. The experiment lasted approximately two hours.

Independent variables / Design

We manipulated the maximum acceleration of the virtual car (A_{max}) as a between-group variable. Participants were assigned to either a *Low-powered* (A_{max} = 2 m/s²), or a *High-powered* (A_{max} = 3.5 m/s²) virtual car. These values were respectively based on the maximum acceleration in second gear of a Fiat Cinquecinto 0.9 and a Subaru Impreza WRX 2009 (Glenn, 2013). The maximum velocity (V_{max} = 35 m/s) was constant between groups. The appearance and size of the driver's car was constant between groups (4.415 m long × 1.740 m wide × 1.475 m high).

We manipulated the minimum satisfying velocity (*MSV*) as a within-participant variable with five values ranging from 21 to 38.5 m/s in 4.375 m/s increments for both the *Low-powered* and *High-powered* groups. The five *MSV* conditions were set by maintaining the lead car's velocity (V_L) at a constant value equal to (*MSV/*1.5) where 1.5 is the ratio of the distance between the driver's car and the obstacle car, to the lead and the obstacle car (see Table 3). The initial positions of the lead (75 m) and obstacle (224.5 m) cars relative to the participant's car on the road-longitudinal axis were constant between trials and so were their visual appearance and size.

MSV was calculated as the quotient of the length of the trajectory required by the driver's car to safely overtake (d_s), and the time until the lead car jeopardized the overtaking maneuver ($t_{overtaking}$) and was formalized as (1):

$$MSV = d_s / t_{overtaking} \qquad (1)$$

We also manipulated the minimum satisfying acceleration (*MSA*) at the start of each trial as a within-participant variable with five values ranging from 0.5 to 2.5 m/s² in 0.5 m/s² increments (for the *Low-powered* group) and from 0.875 to 4.375 m/s² in 0.875 m/s² increments (for the *High-powered* group). *MSA* was computed as the minimum acceleration required to reach *MSV* (before reaching V_{max}). *MSA* was adjusted by manipulating the initial velocity (V_S, in m/s) of the participant's car (from 18.32 to 35 m/s and 16.31 to 35 m/s for the *Low-powered* and *High-powered* groups, respectively) and the lead car's velocity (V_L, in m/s). This changed the time required to reach the *MSV* when adopting the *MSA* ($T_{S,}$ in *s*, see Table 3 and Figure 30). *MSA* was calculated as follows (2):

$$MSA = -(V_{\max} - V_S)^2 \Big/ \left[2 \cdot \left(d_s - V_{\max} \cdot \frac{d_L}{V_L} \right) \right] \qquad \textbf{(2)}$$

Since *MSA* already included the V_{max} and the *MSV* variables, MSA/A_{max} can thus be considered as a "higher-order" property, and MSV/V_{max} as a "lower-order" one. Such a label is inspired from the "higher-order/lower-order" appellation of perceptual variables found in the direct perception theory literature. First, MSA/A_{max} would allow drivers to better identify overtaking opportunities since $MSV/V_{max} < 1$ becomes a necessary but insufficient condition to guarantee safe overtaking. Second, MSA/A_{max} would allow identifying more rapidly overtaking opportunity. Numerical simulations based on 75% of initial velocity revealed that in all of our experimental conditions *MSA* exceeded A_{max} earlier (3.11 and 2.23s on average for A_{max} corresponding to the *low-* and *high-powered* vehicle, respectively) than *MSV* exceeded V_{max} . Perceiving the MSA/A_{max} ratio would thus allow drivers to save time, at least for short range overtaking and small initial velocity (Figure 30).

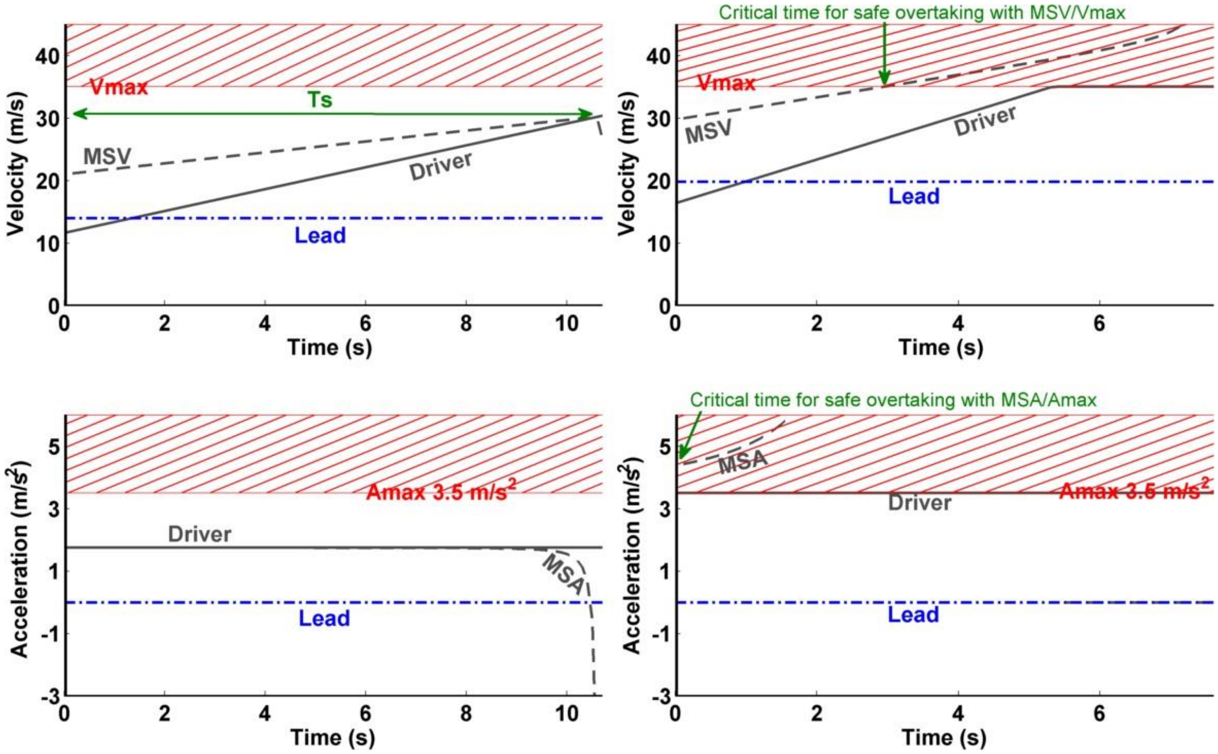

Figure 30. Time course of velocities (upper panels) and acceleration (lower panels) for two overtaking conditions (60% *MSV/Vmax* and 50% *MSA/Amax*, left panels, and 85% *MSV/Vmax* and 125% *MSA/Amax*, right panels). Overtaking is affordable in both conditions based on *MSV/Vmax* but only in the first condition based on *MSA/Amax*. *MSA/Amax* would therefore be a higher order property than *MSV/Vmax*, allowing earlier perception of critical time for safe overtaking.

Note that *MSV* and *MSA* values were selected in order to make overtaking opportunities identical for both groups. MSV/V_{max} and MSA/A_{max} ratios were identical for the two groups, namely: 25, 50, 75, 100 and 125% for MSA/A_{max} and 60, 72.5, 85, 97.5 and 110% for MSV/V_{max} (see Table 3). These conditions were repeated five times in random order for each participant resulting in 125 experimental trials (5 *MSV* conditions × 5 *MSA* conditions × 5 repetitions). Conditions where the MSV/V_{max} and MSA/A_{max} ratio equaled 100% corresponded to the theoretical maximum overtaking opportunity. Hence, 80 of the 125 trials (64%) could result in successful overtaking maneuvers.

For each participant, two lure trials during which another car overtook the participant's car were randomly included. This discouraged the driver from systematically initiating an overtaking maneuver at the start of the trial without checking their rear-view mirror.

Table 3: Overview of experimental conditions and dependent variables according to independent variables manipulated. Gray cells indicate that overtaking was not possible.

All groups (V_{max} = 35 m/s)				Low-powered (A_{max} = 2 m/s²)			High-powered (A_{max} = 3.5 m/s²)		
V_L (m/s)	MSV (m/s)	MSV/V_{max} (%)	MSA/A_{max} (%)	V_S (m/s)	T_s (s)	MSA (m/s²)	V_S (m/s)	T_s (s)	MSA (m/s²)
14	21	60	25	18.32	10.69	0.50	16.31	10.69	0.87
			50	15.64	10.69	1.00	11.63	10.69	1.75
			75	12.96	10.69	1.50	6.94	10.69	2.62
			100	10.34	10.69	2.00	2.68	9.26	3.50
			110*	7.61	10.69	2.50	1.02	8.28	4.37
16.92	25.375	72.5	25	23.16	8.85	0.50	21.50	8.85	0.87
			50	20.94	8.85	1.00	17.62	8.85	1.75
			75	18.73	8.85	1.50	13.83	8.06	2.62
			100	16.55	8.85	2.00	10.68	6.98	3.50
			125	14.34	8.26	2.50	7.67	6.25	4.37
19.83	29.75	85	25	27.86	7.54	0.50	26.44	7.54	0.87
			50	25.97	7.54	1.00	23.21	6.74	1.75
			75	24.09	7.28	1.50	20.56	5.50	2.62
			100	22.43	6.30	2.00	18.37	4.76	3.50
			125	20.91	5.64	2.50	16.36	4.26	4.37
22.75	34.125	97.5	25	32.60	4.80	0.50	31.82	3.63	0.87
			50	31.60	3.40	1.00	30.51	2.57	1.75
			75	30.84	2.77	1.50	29.50	2.10	2.62
			100	30.20	2.40	2.00	28.65	1.82	3.50

			125	29.63	2.15	2.50	27.90	1.62	4.37
25.67	38.5	110	+inf**	35.00	-inf	0.50	35.00	-inf	0.87
			+inf**	35.00	-inf	1.00	35.00	-inf	1.75
			+inf**	35.00	-inf	1.50	35.00	-inf	2.62
			+inf**	35.00	-inf	2.00	35.00	-inf	3.50
			+inf**	35.00	-inf	2.5	35.00	-inf	4.37

Note : Shaded cells indicate that overtaking was not possible. V_{max} = maximum velocity; A_{max} = maximum acceleration; V_L = lead car's velocity; *MSV* = minimum satisfying velocity; *MSA* = minimum satisfying acceleration; V_S = initial velocity; T_S = time required to reach the *MSV* when adopting the *MSA*; Inf = infinite value.
*Such a configuration required the initial velocity of the participant's car to be −1.22 m/s to get a MSA/A_{max} ratio of 125%. As a negative velocity makes no sense in an overtaking situation, we decided to set the initial velocity to 1.02 m/s to reach the maximum theoretical MSA/A_{max} ratio (110%) while still making overtaking impossible.
** The MSA/A_{max} cannot be computed as the driver is bounded by V_{max}.

Dependent variables

For each trial we recorded collisions between the participant's car and either the lead or obstacle cars and also identified the maneuver selected by each participant: overtaking, bailing out, and following. Collisions were then categorized depending on the maneuver in progress at the moment of their occurrence. Collisions during overtaking maneuver were defined as collisions occurring after the driven car has passed the lead car, namely when cutting in the trajectory of the lead car or colliding the obstacle car. Collision during bailing out (namely, during a lateral excursion from the left to the right lane) and following maneuvers resulted exclusively in a crash into the lead. The collision frequency and overtaking frequency (both successful maneuvers and maneuvers that resulted in collision) were calculated for each participant and each condition. A frequency of 100% indicates that the overtaking maneuver succeeded in each of the five trials for a given condition.

Statistics

Our initial analyses aimed to find whether collisions were caused by a reliance on any of the experimental factors. Therefore, a three-way mixed-design ANOVA was performed on collision frequency induced by overtaking maneuvers using A_{max} as the independent variable (two modalities: *Low-powered* and *High-powered*) and repeated measures on MSV/V_{max} (four modalities, ranging from 60 to 97.5% in 12.5% increments) and MSA/A_{max} (five modalities, ranging from 25 to 125% in 25% increments). Data from trials where MSV/V_{max} was equal to 110% were excluded from the analyses since the corresponding MSA/A_{max} values were always *+inf*. Individual percentages of collision frequency in conditions that showed no within-participants variance (i.e., conditions for which no participant was found to collide with surrounding vehicles) were replaced by random values ranging from 0 to 1 (whereas frequency ranged from 0 to 100% in other conditions). This occurred during one condition (MSV/V_{max} = 60% × MSA/A_{max} = 25%) for the analysis of collision frequency.

Secondly, we analyzed whether drivers in the *Low-powered* and *High-powered* groups initiated similar overtaking maneuvers as a function of the MSA/A_{max} ratio. Individual overtaking frequencies were fitted (using factorial regression) by adjusting the coefficients *a–d* in the function defined by (3) :

$$f(x,y) = a \cdot x + b \cdot y + c \cdot x \cdot y + d \qquad \textbf{(3)}$$

in which $f(x,y)$ corresponds to the probability of observing an overtaking maneuver, x is either *MSV* or MSV/V_{max} and y is either *MSA* or MSA/A_{max}. In this equation, the coefficients a and b express a proportional influence of x and y on overtaking frequency; c reflects the $x \times y$ interaction and d is a constant that acts as a vertical offset modulating the average frequency of overtaking maneuvers. These adjustments were used to determine which of the coefficients *a–d* varied as a function of A_{max}. Separate one-way independent group ANOVAs (A_{max}) were then performed on individual *a–d* coefficients (expressed as a function of *MSV* and *MSA*) in order to quantify between-group differences in the selection of overtaking maneuvers. In addition, separate one-way ANOVAs (A_{max}) were performed on individual *a–d* coefficients expressed as a function of MSV/V_{max} and MSA/A_{max} to test the hypothesis that behavior was similar across groups when *MSV* and *MSA* were expressed as a ratio of V_{max} and A_{max}, respectively.

Finally, a three-way mixed-design ANOVA was performed on overtaking frequency, using A_{max} as the independent variable and repeated measures on MSV/V_{max} and MSA/A_{max}. Moreover, multiple regressions were carried out on various combinations of variables based on their assumed influence on the success of an overtaking maneuver. For all statistical analyses, *p* was 0.05. Data from lure trials in which another car overtook the participant's car at the beginning of the trial were excluded from all analyses. Individual percentages of overtaking frequency in conditions that showed no within-participants variance (i.e., conditions for which no driver was shown to perform an overtaking maneuver) were replaced by random values ranging from 0 to 1. This occurred during three conditions (MSV/V_{max} = 60, 72.5 and 85% × MSA/A_{max} = 125%) for the analysis of overtaking frequency. For all tests, partial effect sizes were computed (η^2_p) and post-hoc comparisons were conducted using Newman-Keuls a posteriori tests.

RESULTS

Collisions

Our first hypothesis assumed that if drivers do perceive an overtaking affordance, they would only initiate the maneuver when overtaking is possible. Drivers in the *Low-powered* and *High-powered* groups collided with surrounding cars in 15.8% and 14.4% of trials, respectively. Among them, the small percentage of collisions resulting from overtaking attempts (2.84 and 3.56% of trials for the *Low-powered* and *High-powered* groups, respectively) tended to confirm that participants could accurately distinguish whether the situation allowed safe overtaking or not. Collisions most frequently occurred during bailing out maneuvers (11.20 and 10.04% for the *Low-powered* and *High-powered* groups, respectively), when drivers hastened their return to the right hand lane while colliding the left side of the lead car. Collisions infrequently occurred during following maneuvers (1.78 and 0.8% for the *Low-powered* and *High-powered* groups, respectively), when driver crashed into the lead car rear bumps.

Our second hypothesis was that the exclusive use of MSV/V_{max} without care of MSA/A_{max} would lead drivers to initiate unsafe overtaking maneuvers. Specifically, they would decide to overtake when MSV/V_{max} indicated a safe overtaking opportunity (e.g., MSV/V_{max} equal to 97.5%), while at the same time MSA/A_{max} (e.g., MSA/A_{max} equal to 125%) indicated that overtaking was unsafe. A three-way ANOVA (A_{max} × MSV/V_{max} × MSA/A_{max}) with repeated measures on MSV/V_{max} and MSA/A_{max} was performed on the frequency of collisions resulting from overtaking maneuvers. This ANOVA revealed a significant MSV/V_{max} × MSA/A_{max} interaction ($F(12,192) = 1.98$; $p < 0.05$; $\eta^2_p = .11$). Newman-Keuls post-hoc analyses showed that collisions occurred significantly more frequently in a small, specific set of conditions where

MSA/A_{max} was equal to 50 or 100% and MSV/V_{max} was equal to 97.5% (collision frequency equal to 13.33 and 20% for the *Low*- and *High-powered* groups, respectively; $p < 0.05$). No significant differences were found in other MSV/V_{max} conditions for which MSA/A_{max} was superior to 100% (collision frequency equal to 1.67 and 1.67%; $p > 0.05$). Whereas a large number of collision - especially in conditions where $MSA/A_{max}>1$ - would indicate that drivers randomly attempted to perform overtaking maneuver, our results led us to conclude that participants avoid collisions by perceiving overtaking opportunities on the basis of the MSA/A_{max} ratio.

Overtaking frequency

Our third hypothesis was that if drivers rely on MSA/A_{max} overtaking frequency would vary as a function of *MSA* and A_{max}.

Figure 31A shows average overtaking frequencies plotted as a function of *MSA* and *MSV* manipulations for the *Low-powered* (black surface) and *High-powered* groups (gray surface), respectively. As expected, overtaking frequency decreased with increases in *MSA* for both groups of drivers but also unexpectedly with increase of *MSV*. In addition, overtaking frequency seemed to overlap for both groups on the *MSV* but not the *MSA* axis. The absence of overlap on the *MSA* axis is indicated by the double-headed arrow. This finding not only confirms that drivers changed the way they initiated overtaking maneuvers as a function of MSV/V_{max}, as already evidenced, but most importantly suggests that they were also sensitive to *MSA* and A_{max}.

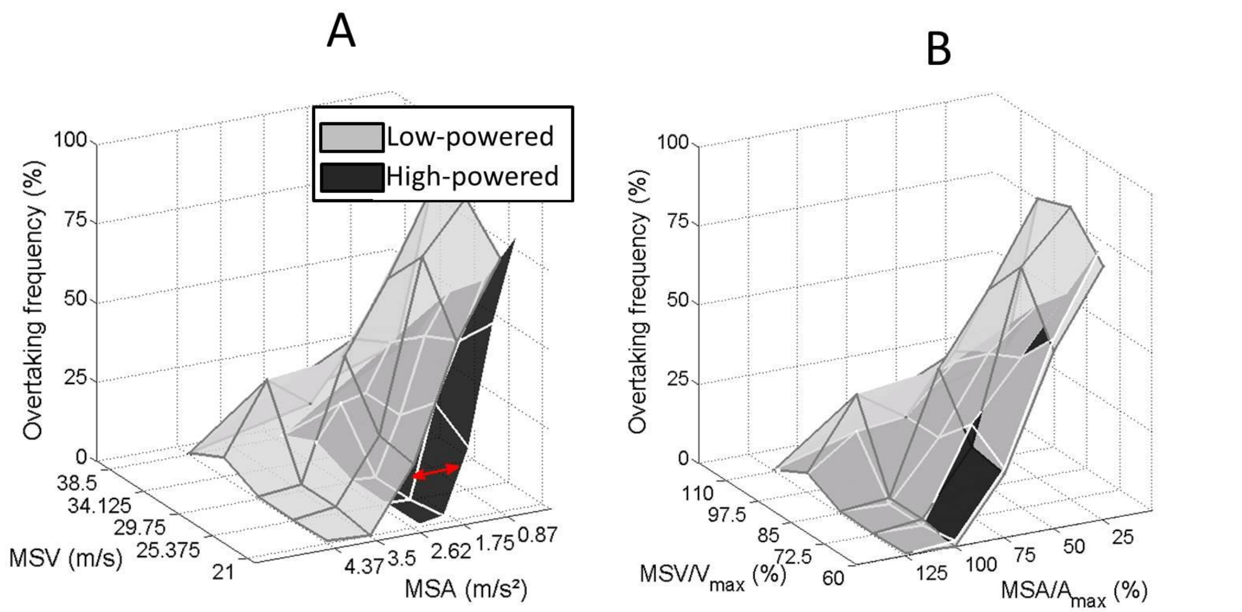

Figure 31. Average frequency of overtaking maneuvers plotted as a function of *MSV* and *MSA* (panel A), and *MSV/Vmax* and *MSA/Amax* (panel B) for the Low-powered (black) and High-powered (gray) groups.

We then fitted overtaking frequency with equation (3) using *MSV* and *MSA* as predictors. Individual adjustments led to average R^2 values equal to 0.76 and 0.71 for the *Low-powered* and *High-powered* groups, respectively.

Table 4. Average inter-individual values of the best a–d coefficients used to fit individual overtaking frequency as a function of *MSA* and *MSV* and *MSA*/*Amax* and *MSV*/*Vmax*. Significant differences between-group are indicated by asterisks.

Predictors / Coefficient	***MSV* and *MSA***		
Coefficient	**Low-powered**	**High-powered**	**F value, *p***
a (*MSV*)	19.10	-4.27	0.99, $p>0.05$
b (*MSA*)	-100.71	-62.57	14.87, $p<0.05$*
c (*MSV*×*MSA*)	2.38	1.41	7.58, $p<0.05$*
d (vertical offset)	58.21	67.02	0.09, $p>0.05$
Predictors / Coefficient	**MSV/V_{max} and MSV/A_{max}**		
a (MSV/V_{max})	-1.57	-1.49	0.04, $p>0.05$
b (MSA/A_{max})	-2.01	-2.19	0.45, $p>0.05$
c ($[MSV/V_{max}] \times [MSA/A_{max}]$)	0.02	0.02	0.04, $p>0.05$
d (vertical offset)	58.21	67.02	0.09, $p>0.05$

One-way ANOVAs (A_{max}) were performed separately on each of the coefficients to highlight the respective contribution of *MSA*, *MSV* and *MSV*×*MSA* in overtaking frequency as a function of group (cf. Table 4). These ANOVAs revealed no significant main effect of A_{max} on the coefficient *a* (F (1, 16) = 0.99; $p > 0.05$). The absence of between-group differences on *a* confirms that both groups, with the same V_{max}, responded in the same way to the manipulation of *MSV*. However, the ANOVA revealed a significant main effect of A_{max} on the coefficient *b* (F (1,16) = 14.87; $p < 0.05$; $\eta^2_p = 0.48$). The negative value of *b* for the *High-powered* group is lower than for the *Low-powered* group. This underlines that an identical increase in *MSA* resulted in a bigger decrease in overtaking frequency for the *Low-powered* than for the *High-powered* group. The higher positive value of *c* for the *Low-powered* compared to the *High-powered* group also suggests that overtaking frequency was influenced by the *MSA* × *MSV* interaction as a function of group: $F(1, 16) = 7.58$; $p < 0.05$; $\eta^2_p = 0.32$. Hence, for a given *MSV* condition, the change in overtaking frequency as a function of *MSA* is more pronounced for the *Low-powered* than the *High-powered* group. These results show that, when expressed as a function of *MSV* and *MSA*, overtaking maneuvers are initiated differently as function of group (A_{max}).

Figure 31B shows a transformation of Figure 31A, in which each *MSA* and *MSV* condition was divided by A_{max} (2 and 3.5 m/s² for the *Low-powered* and *High-powered* groups, respectively) and V_{max} (35 m/s). It is important to note that overtaking frequency dropped to 0% for both groups when MSV/V_{max} and MSA/A_{max} exceeded 100% (i.e., when *MSV* and *MSA* required for successful overtaking were greater than the car's V_{max} and A_{max}). This suggests that drivers in both groups reliably perceived situations where overtaking requirements exceeded their car's capabilities. Moreover, the two overtaking frequencies surfaces overlap, suggesting that the groups behaved similarly for a given MSA/A_{max} ratio.

We then fitted individual overtaking frequencies with equation (3); in this case variance in overtaking frequency results from the influence of MSV/V_{max} and MSA/A_{max}. This analysis determined whether the between-group differences in overtaking frequency (due to the manipulation of *MSA*) found in earlier analyses vanished when MSA/A_{max} was taken into account.

One-way ANOVAs (A_{max}) were separately performed on *b* and *c* coefficients. These analyses highlighted the identical contribution of MSA/A_{max} and MSV/V_{max}×MSA/A_{max} interactions in overtaking frequency for both groups (cf. Table 4). ANOVAs revealed no significant effect of A_{max} on *b* and *c* (F (1, 16) < 0.45; $p > 0.05$; *ns*). These results confirm that between-group differences in overtaking frequency that are due to the manipulation of *MSA*, vanish when *MSA* is expressed as a scale that integrates A_{max}. Hence, the decision to overtake appears to be similar among groups when the overtaking affordance is expressed through MSA/A_{max} and MSV/V_{max} ratios.

While we predicted that between-group differences in overtaking frequency expressed as a function of *MSA* would vanish when expressed as a function of MSA/A_{max}, we did not expected between-group differences in coefficient that fit overtaking frequency due to the MSA/A_{max} × MSV/V_{max} × A_{max} interaction. This effect can be seen in Figure 31, and was revealed by a three-way mixed-design ANOVA performed on individual values of overtaking frequency: F(12,192) =

2.52; $p < 0.05$; $\eta^2_p = 0.14$. Post-hoc analyses showed that the *High-powered* group overtook significantly more frequently in a small and specific set of conditions that combined MSA/A_{max} equal to 50 or 25% and MSV/V_{max} equal to 72.5% or 85% ($p < 0.05$), respectively.

We suspected that other, underlying, variables were the reason for these differences as MSV/V_{max} and MSA/A_{max} were identical for all groups. Separate multiple regression were performed for overtaking frequency, MSA/A_{max} and candidate variables (MSV/V_{max}, T_s, V_s, MSV-V_s, and $(MSV$-$V_s)/T_s$). Each of these variables relies on the driver's speed, and the combination of multiple variables allowed us to isolate those that were most relevant. The results of these analyses are summarized in Table 5.

Table 5. Results of multiple regressions between overtaking frequency, *MSA/Amax* (Predictor 1) and *Ts*, *Vs*, *MSV-Vs*, and (*MSV-Vs*)/*Ts* (predictor 2). Significant differences are indicated with asterisks.

Predictor 1	F value, *p*	Predictor 2	F value, *p*	Adjusted R^2
MSA/A_{max}	473.17, p<.05*	MSV/V_{max}	8.42, p<.05*	0.57
MSA/A_{max}	420.33, p<.05*	T_s	5.96, p<.05*	0.57
MSA/A_{max}	425.98, p<.05*	V_s	3.18, p>.05	0.57
MSA/A_{max}	251.15, p<.05*	MSV-V_s	0.01, p>.05	0.56
MSA/A_{max}	214.79, p<.05*	$(MSV$-$V_s)/T_s$	1.96, p>.05	0.56

The analyses revealed that overtaking frequencies were significantly correlated with two pairs of variables: MSA/A_{max} + MSV/V_{max} and MSA/A_{max} + T_s, i.e., the time required to reach *MSV* starting from the current velocity by accelerating at *MSA* (see between-group changes in T_s in Table 3). As T_s was the only candidate variable that had a significant influence in the regression ($p < .05$), an adjusted R^2 that was as high as the initial variable MSV/V_{max} (0.57), and varied between group, we concluded that drivers seemed to combine MSA/A_{max} and T_s to accurately perceive overtaking opportunities. The combined influence of MSA/A_{max} and T_s on overtaking frequency could be the cause of the significant between-group differences in overtaking frequency observed in Figure 31, and such an explanation was confirmed by three-way mixed-design ANOVAs ($MSV/V_{max} \times MSA/A_{max} \times A_{max}$) performed on overtaking frequency.

DISCUSSION

We investigated the reliability of a driver's decision to overtake (or not) in an effort to clarify the causes of overtaking accidents. In line with Morice et al. (2015), we hypothesized that drivers would safely overtake (or not) based on their perception of an overtake-ability affordance. However rather than using the maximum velocity of the driver's car (V_{max}) as a scale for perceiving the minimum satisfying velocity (*MSV*) needed to overtake the lead car, we extended the study of Morice et al. by hypothesizing that drivers would also rely on a more relevant capability: the maximum acceleration of their car (A_{max}). We predicted that drivers would use A_{max} to assess the minimum satisfying acceleration (*MSA*) required to accelerate from their current velocity to the *MSV* before reaching their car's V_{max}. We showed that driver's decision not only vary with MSA/A_{max}, but also (and unexpectedly) as a function of *Ts*. We discuss these results in the following sections.

Driver's sensitivity to MSA/A_{max}

We hypothesized that the perception of $MSV/V_{max} < 1$ was a necessary but insufficient condition to guarantee safe overtaking. We thus predicted that relying solely on MSV/V_{max} would lead drivers to make mistakes in estimating overtaking maneuvers. In particular, they would initiate overtaking maneuvers in situations in which $MSV/V_{max} < 1$, but there would be collisions with other vehicles in situations that combined $MSV/V_{max} < 1$ and $MSA/A_{max} > 1$. On the other hand, we anticipated that the perception of $MSA/A_{max} \leq 1$ was a necessary and sufficient condition to guarantee safe overtaking.

Our analyses of collisions revealed results that are consistent with the use of MSA/A_{max} as an affordance to initiate overtaking maneuvers. Collisions were infrequent and occurred in a few set of "risky" conditions (e.g., MSV/V_{max} = 97.5 and MSA/A_{max} = 100%). This suggested that drivers reliably distinguished safe from unsafe overtaking situations. The overall frequency of collisions in our study was similar to the frequency of collisions reported in real-world overtaking accident reports (Wilson & Best, 1982) and laboratory studies (Gordon & Mast, 1970; Gray & Regan, 2005).

Moreover, our analyses of overtaking frequencies confirm the use of MSA/A_{max}. Indeed, the frequency of overtaking consistently dropped to 0% when *MSV* and *MSA* exceeded V_{max} and A_{max}, respectively. Furthermore, both *Low-powered* and *High-powered* groups behaved quite similarly when overtaking frequencies were plotted as a function of MSV/V_{max} and MSA/A_{max}. Similar results were reported by Warren (1984), and Warren and Whang (1987) in the perception of aperture crossing and stair climbing possibilities. These studies showed that similarities in approach behavior (despite variation in shoulder width and leg length) were due to the scaling of the aperture and stairs by the body property in question. Here, similarities in overtaking behavior are due to the scaling of overtaking requirements to the actions capabilities V_{max} and A_{max}.

Why did drivers not rely entirely on MSA/A_{max}?

In our experiment, reaching *MSV* before it exceeded V_{max} was a necessary but not sufficient condition for a successful overtaking maneuver while reaching *MSA* before it exceeded A_{max} was a sufficient condition. In other words, MSA/A_{max} was a high-order affordance making MSV/V_{max} useless. Identical MSA/A_{max} ratios should thus lead expert drivers to perceive overtaking opportunities as identical, independently of MSV/V_{max}. However, we found an unexpected sensitivity to the time required for the car to reach *MSV* from its initial velocity (T_s). Drivers in the *High-powered* group seemed more likely to overtake than drivers in the *Low-powered* group, while overtaking opportunities were theoretically identical for both groups. Moreover, the three-way mixed-design ANOVA of overtaking frequencies revealed that they varied as a function of the $MSV/V_{max} \times MSA/A_{max} \times A_{max}$ interaction. Finally MSA/A_{max} and T_s were both found to be significant and to best predict overtaking frequencies among candidate variables. Since T_s is a property close to MSV/V_{max}, the results are consistent with the ones previously reported by Morice et al, maybe due to the tiny improvement of accuracy of MSA/A_{max} as compared to MSV/V_{max} for usual drivers.

The "higher-order" label of MSA/A_{max} was given in reference to perceptual variables that perfectly specify some physical properties (see Jacobs, Michaels, & Runeson, 2000 and; Michaels & de Vries, 1998 for smart demonstrations) because it perfectly inform drivers about their driving possibility. It was hypothesized to be opposed to the "lower-order" property *MSV/Vmax*, whose correlation with overtaking possibility decrease as overtaking distance and time decrease and when the necessity to accelerate increase. In theory, the affordance-based control framework (Fajen, 2007a) allows an infinite range of behaviors and chances of success provided that the "ideal" state remains below the action capability boundary. However, as the ideal state (*MSV* in our case) moves closer to the boundary (V_{max}), the number of possible behaviors decreases and temporal constraints increase. Therefore, if drivers do not have to perform large acceleration because they drive at a velocity close to *MSV* (as in the Morice et al. 2015), MSV/V_{max} co-varies with the number of possible behavior and informs quite accurately drivers about their overtaking possibility.

However, the present study required larger acceleration than in the Morice et al. (2015) to perform safe overtaking. Therefore, drivers may have relied on T_s as a lower-order estimation of the temporal constraints of the overtaking situation. In other words, drivers may have used T_s to perceive their degree of freedom to follow *MSA* and to determine their safety margin. In line with the affordance-based control framework, T_s thus enables drivers to quantify the "safe region" (Fajen, 2005b) in order to select and regulate the most appropriate action mode (e.g., overtaking, following, etc.) given the temporal constraints of the overtaking situation. Therefore, drivers may be in an intermediate step of perceptual learning in which they mix between higher-order and lower-order variables. Previous results indeed revealed that the dynamics of perceptual learning is quite fast but not instantaneous (Bastin, Fajen, & Montagne, 2010; Fajen, 2007b; Flach et al., 2011; McKenna, 2004). The introduction of an unbeknownst increase or decrease of maximum velocity and acceleration would thus be required. Such a methodology, in line with experimental evidence of rapid recalibration of agent to their maximum deceleration when braking (Fajen, 2007b) or maximum velocity when intercepting target (Bastin et al., 2010), would serve as an ultimate demonstration of participant level of calibration.

Limitations and Future Research

The present study refines the portrayal of the variables implied in the perception of the overtaking possibility with regards to the Morice et al. (2015) study. Nevertheless, the conclusions drawn need to be nuanced with regards to the following limits. We believe that some poor performances of the devices used (e.g., limited field of view and low resolution of the head mounted display) do not jeopardize the validity of this study, since it kept invariant the essence of real life visual world. On the contrary, some features of the virtual simulation used (e.g., unconventional operation of the steering wheel, stationary vehicle on the left-hand lane) may limit the generalizability to real passing behavior by generating for instance more collisions during bailing out maneuvers than in real driving or more 'risky' overtaking attempts than with speed fluctuations of the oncoming traffic, respectively. Finally, and maybe more importantly, the use of a fixed-base driving simulator may have weakened the possible bridge between the perceptual process evidenced in the present experiment and those used in natural environments. Indeed, it is noteworthy that visual and non-visual contributions may contribute to the perception of action-scaled affordances, as the minimum required velocity to pass through shrinking aperture (Fajen & Matthis, 2011). For instance, in real life overtaking, vestibular information may help drivers to retrieve from visual relative displacements of objects components due to their self-motion (stimulating the vestibular system) from those due to the movement of surrounding (e.g., lead) cars. Such a limitation should lead the researcher interested by practical issues associated with training and design, as well as keen on the understanding of decision-making process to be cautious with our results (Flach et al., 2011).

Demonstrating that depending on expertise drivers rely on the MSV/V_{max} and/or the MSA/A_{max} ratios when deciding to overtake or-not is the first pre-requisite to evidence that drivers perceive an overtaking-ability affordance. A second step in the experimental affordance-based approach of overtaking would consist in identifying the source of information that supports the overtake-ability affordance. This would be in line with the agenda followed by previous research on body-scaled affordances (Warren & Whang, 1987) and action-scaled affordances (Fajen, 2005b; Fajen & Matthis, 2011). We believe that perceiving the overtake-ability cannot result from a separate perception of MSA and A_{max} followed by a comparison between them. Indeed, such process would first imply for the agent to be sensitive to an acceleration (i.e., the MSA) or a differential between velocities, but the poor ability of the human perceptual system to reliably detect acceleration (Watamaniuk & Heinen, 2003; Werkhoven, Snippe, & Toet, 1992) discredit such strategy. Perceiving the overtake-ability through comparison between separate perception of *MSA* and *Amax* values would secondly disavow the main affordance hypothesis assuming that action boundaries provide critical references for perceiving directly possibility for action. We thus suggest that *MSA* is perceived directly in units of A_{max}. When properly calibrated, sources of information about *MSA* should indicate to drivers the percentage of A_{max} necessary to safely overtake. Our definition of the overtaking-ability affordance (*MSA* required to accelerate from the current velocity to the *MSV* before it exceed V_{max} scaled by A_{max}) is expected to provide a starting point and landmarks for identifying candidate perceptual information's that drivers could use to perceive MSA/A_{max}. Indeed, perceptual support of properties analog to *MSV* for successful interception (Bastin et al., 2010) and passing through aperture (Fajen & Matthis, 2011) exist, based on optical specifications of passing distance, time-to-passage and current speed. The optical specification of *MSA* however remains to be identified.

To be fully consistent with real life overtaking behavior, future research should investigate drivers' ability to exploit changes in their action limits when changing gear. Are drivers able to be aware that the current gear, unlike the lower gear, is unable to provide enough A_{max} to reach *MSA* and decide to activate a lower gear in order to successfully perform a safer overtaking maneuver? In the same vein, it would be interesting to investigate drivers' ability to calibrate with changes in their maximum acceleration not only with gear changes but also with the velocity changes for a given gear.

Practical implications

Conceiving Advanced Driver Assistance System (ADAS) dedicated to overtaking maneuvers is a concern nowadays. Their common principle consists in helping the driver to judge whether a gap will be safe enough for overtaking. However, few devices exist and most studies are limited to task analysis and numerical simulation of controller behavior (Arvind Raj, Dinesh, Manish, & Sasikala, 2013; Barańska, 2010; Hegeman, Tapani, & Hoogendoorn, 2009). To our knowledge, the few completed prototypes rely on road features (e.g., road curvature, legal overtaking restrictions, speed limits) and actions limits (e.g., driver's car maximum velocity and sometime a maximum "comfortable" acceleration) but ignore the obstacle traffic (Loewenau et al., 2006; Milanes et al., 2012; Naranjo, Gonzalez, Garcia, & de Pedro, 2008). Oppositely, when taking into account the oncoming traffic, they use a behavioral database and pre-programmed threshold (Barańska, 2010; Hegeman et al., 2009) to compute the spatio-temporal constraints and remains at the step of simulations (Ruiz, Gil, Naranjo, Suárez, & Vinagre, 2007; Yang & Zhou, 2008).

We believe that the effectiveness of ADAS for overtaking relies on the coherence of the solution with human perception. Individuals must agree with the recommendations of the device (Wiener, 1981) rather than trying to get round it (Stanton & Pinto, 2001). Therefore, if future devices are to be fully efficient they must rely on the same perceptual variables as those used by humans, albeit with more sensitive sensors. Our work has shown that in theory MSA/A_{max} is sufficient to discriminate between safe and unsafe situations. However, if they are to be consistent with the decisions taken by humans, any overtaking assistance device should include a safety margin based on *Ts*.

In conclusion, this study extends the one of Morice et al. (2015) by revealing that drivers are not only sensitive to their car's maximum velocity by also to its maximum acceleration for perceiving overtaking possibility, consistently with the affordance-based framework. From a practical point of view, overtaking assistance devices should include the variable MSA/A_{max} - that uses these underlying actions limits for determining the driver's overtake possibility - to be fully accepted by drivers.

KEY POINTS

- We formalize an overtake-ability affordance based on the minimum acceleration required for safe overtaking
- Drivers take the maximum acceleration and velocity of their vehicle into account in overtaking maneuvers
- The affordance-based framework offers a new perspective for safe overtaking maneuvers