Le simulateur de conduite une validité écologique expérimentale

II.1.1 La réalité virtuelle

Les trois expérimentations présentées dans ce travail ont eu recours à l'utilisation de la réalité virtuelle par le biais d'un simulateur de conduite à base fixe. Bien que n'ayant pas eu connaissance d'une telle technologie, J. J. Gibson (1986) insistait déjà sur la nécessité d'« amener le monde réel dans le laboratoire ». Par ailleurs, comme le précisent de très nombreux spécialistes de la réalité virtuelle (CRTRV, 2004; Fuchs, 1996) : « *la finalité de la réalité virtuelle est de permettre à une personne (ou à plusieurs) une activité sensori-motrice et cognitive dans un monde artificiel, créé numériquement, qui peut être imaginaire, symbolique ou une simulation de certains aspects du monde réel*». Cette technologie et les finalités qui lui sont associées sont donc en totale adéquation avec la conception écologique à laquelle nous souhaitons nous référer dans la tâche de dépassement automobile.

En outre, la réalité virtuelle présente de nombreux avantages dans l'étude des comportements perceptivo-moteurs tels que la simulation de certains aspects du monde réel (e.g., prise de décision dans un temps limité) ou encore la simulation de comportements automobiles sans danger physique pour le conducteur. Par ailleurs, l'analyse des comportements automobiles « en-ligne » permet à l'expérimentateur d'identifier plus précisément les comportements perceptivo-moteurs mis en œuvre. La réalité virtuelle permet également de créer et de manipuler de nombreuses propriétés environnementales (e.g., texture de route, vitesse des véhicules, densité du trafic routier, etc.) ainsi que de reproduire les scénarios élaborés.

L'utilisation de la réalité virtuelle dans le domaine des sciences du comportement permet ainsi de faire coexister la validité écologique d'une étude en laboratoire et le contrôle expérimental nécessaire à l'étude objective d'un comportement perceptivo-moteur (Loomis, Blascovich, & Beall, 1999; Mestre, 2006). En d'autres termes, le participant est en mesure de contrôler et de transformer activement par son action l'information contenue dans l'environnement virtuel. Conformément à notre cadre conceptuel, les déterminants perceptivo-moteurs du dépassement automobile pourront être étudiés à travers une perception active des participants.

Les nombreuses études attestant la validité de la réalité virtuelle dans l'observation des comportements dits « naturels » n'ont pas empêché de vifs débats concernant la pertinence d'une telle technique dans l'observation des comportements humains (Alicandri, 1994; Desmond & Matthews, 1997; Ellingrod et al., 1997; Fraser, Hawken, & Warnes, 1994; Mestre, 2006; Tarr & Warren, 2002; Underwood, Crundall, & Chapman, 2011; Van Winsum & Brouwer, 1997; Van Winsum & Godthelp, 1996).

II.1.2 Le simulateur de conduite

La Figure 20 ci-dessous représente une vue d'ensemble du simulateur de conduite (Panneau A) et de la scène virtuelle diffusée aux participants (Panneau B) dans les quatre expériences présentées ultérieurement. Les participants prennent place dans un siège de conduite (Mobsim, France) et manipulent deux pédales (Trackstar 6000 GTS) avec leur pied droit permettant l'accélération et le freinage. Ils conduisent un véhicule virtuel standard (ECCI, Trackstar 6000 GTS). Les participants peuvent augmenter leur vitesse courante en appuyant sur l'accélérateur à partir de sa position initiale et freiner en appuyant sur la pédale de frein. Une particularité est introduite dans la troisième expérience: les participants peuvent manipuler l'accélération maximale de leur véhicule à l'aide d'un levier de vitesse (ECCI, Trackstar 6000 GTS). L'utilisation de deux rapports de vitesse est alors autorisée : une 3$^{\text{ème}}$ et une 4$^{\text{ème}}$ vitesse.

Pour atteindre une vitesse, une accélération ou encore un freinage maximal, les conducteurs doivent appuyer sur la pédale associée de façon à se trouver « pied au plancher ». Les valeurs de vitesse, accélération et freinage courantes sont quant à elles liées à la position de la pédale associée, de la position totalement relâchée à la position « pied au plancher ». Le volant agit comme un interrupteur : les participants contrôlent seulement leurs mouvements de la gauche vers la droite en tournant le volant de façon à dépasser un seuil d'activation préprogrammé de ± 30°. Deux boutons localisés sur le côté gauche et sur le côté droit du volant ainsi qu'un bouton central affichent brièvement – à la demande du conducteur – les rétroviseurs de côtés et le rétroviseur central.

Une scène virtuelle est diffusée en ligne à l'aide d'un logiciel de réalité virtuelle propre au laboratoire (*ICE*) exécuté sur un ordinateur durant l'expérimentation (*Microsoft® Windows® XP Pro® SP2, Intel® Pentium®* 4@3.2 *GHz CPU*, 3.5 G0 de *RAM*, *Nvidia GeForce* 6600 GT). Pour ce faire, le logiciel intègre un signal USB généré par les mouvements de pédales et de volant. La scène virtuelle est projetée dans un casque de réalité virtuelle 3D (*Hi-res 900 stéréo*) avec une fréquence de rafraîchissement de 75Hz et une résolution de 800×600 pixels. Ce casque de réalité virtuelle fournit un champ de vision de 31.2° diagonale pour chaque œil. Un système électromagnétique de suivi des rotations céphaliques (6 DDL, *Flock of Birds*) lie le point de vue dans le monde virtuel aux rotations céphaliques du conducteur, tout en conservant un point fixe d'observation (0.975m au-dessus du sol) au centre du siège conducteur.

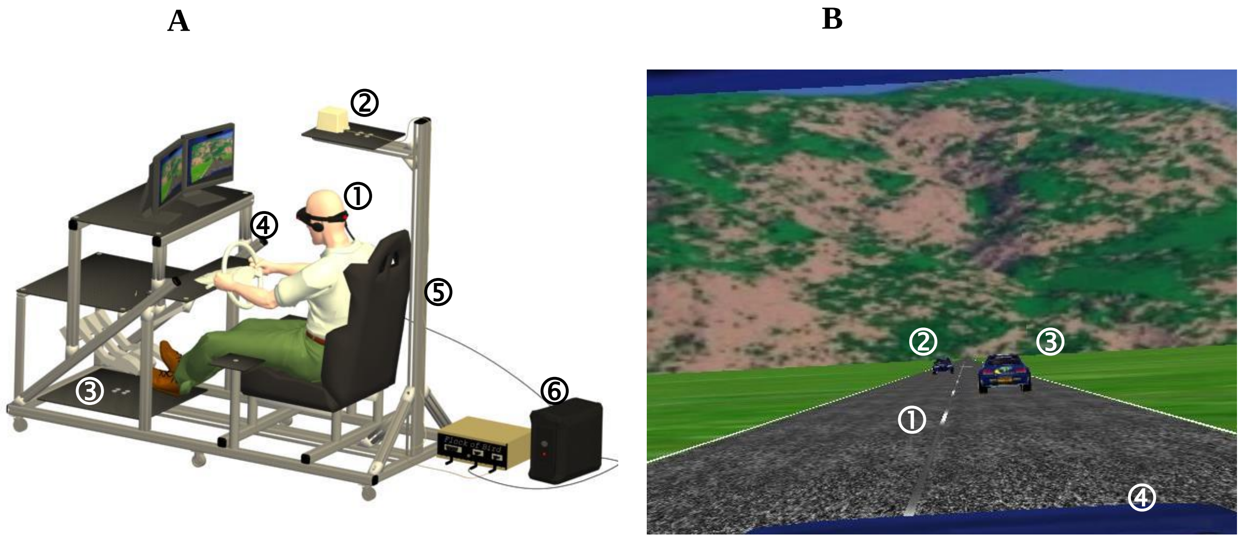

Figure 20 : (A) Le dispositif de réalité virtuelle et ses composants comprennent (1) un casque de réalité virtuelle (Hi res 900 stereo, Cybermind corp.) ; (2) un dispositif de capture de position (Flock Of Bird, Ascension Inc.) ; (3, 4) un pédalier et un volant (ECCI, Trackstar 6000 GTS) ; (5) un siège de voiture ; et un moteur de réalité virtuelle (6). (B) Scène virtuelle typique montrant (1) Lignes pointillées (2) Obstacle (3) Voiture Meneuse (4) Participant.

À l'aide de questionnaires relatifs aux cybers malaises (Kennedy, Lane, Berbaum, & Lilienthal, 1993), nous vérifions l'influence de la présence – plus subjective – des participants. La présence est définie comme « le sentiment authentique d'exister dans un monde autre que le monde physique où notre corps se trouve » (Bouvier, 2009). D'après l'auteur, le sentiment de présence est une expérience subjective, consciente, qui dépend de facteurs internes et externes à l'utilisateur. Cet effet découle de l'ensemble des caractéristiques objectives de la réalité virtuelle (i.e., immersion) énoncées précédemment.

II.2 Configuration environnementale et propriétés d'intérêt

II.2.1 La situation de dépassement automobile

Dans l'ensemble des quatre expériences, la présence d'éléments virtuels de l'environnement – i.e., véhicule *leader* (à doubler), véhicule obstacle, véhicule sujet, ligne de départ et ligne d'arrivée – et leurs dimensions physiques sont identiques. À l'inverse, leurs agencements dans l'espace – i.e., position et vitesse – évoluent en fonction des conditions expérimentales. La scène virtuelle (Figure 20, Panneau B) est composée d'une route à double sens de circulation d'une largeur de 3.5 m, d'un véhicule *leader* mesurant 4.415 m de long et 1.740 m de large et d'un véhicule obstacle immobilisé sur la voie de gauche. Les dimensions du véhicule obstacle sont égales à celle du véhicule *leader*. Le dimensionnement de la route à double sens et des lignes pointillées ou continues s'appuie sur la réglementation française en cours.

Le tableau (Tableau 2) ci-dessous indique les positions initiales des différents éléments virtuels de l'environnement dans l'ensemble des expériences. Chaque expérimentation propose pour chaque essai une phase d'approche. Elle permet aux conducteurs d'atteindre les vitesses requises au lancement de l'essai (Expérimentation 1). À ce stade, aucune voiture virtuelle n'est visible dans la scène visuelle.

Une fois le franchissement de la ligne de départ réalisé à la vitesse minimum satisfaisante (i.e., vitesse minimal pour réussir le dépassement en toute sécurité), une voiture à doubler roulant à vitesse constante (i.e., véhicule *leader*) et une voiture à éviter, immobile, (i.e., véhicule obstacle) apparaissent dans l'environnement routier virtuel, respectivement dans la voie de circulation du véhicule sujet et dans la voie opposée (Tableau 2).

Les conducteurs disposent alors d'une dizaine de secondes, avant d'atteindre la ligne d'arrivée, pour percevoir la faisabilité du dépassement et prendre la décision de l'initier tout en évitant les véhicules virtuels (*leader* et obstacle). Dans l'ensemble des expériences, un dépassement automobile est considéré réussi si le conducteur parvient à dépasser le véhicule *leader*, à éviter le véhicule obstacle, et à franchir la ligne d'arrivée sans encombre. Une fois l'essai terminé, un nouvel essai démarre à la suite jusqu'à ce que le bloc expérimental soit terminé.

Tableau 2 : Configuration initiale des éléments virtuels de l'environnement pour chaque expérience.

	CAMPAGNES EXPÉRIMENTALES		
POSITION INITIALE DES ÉLÉMENTS VIRTUELS (EN M)	Expérimentation 1	Expérimentation 2	Expérimentation 3
Véhicule sujet	0	0	0
Véhicule leader	100 + Phase d'approche	70.1 + 45	70.1 + 45
Véhicule obstacle	246.7 + Phase d'approche	224.5 + 45	224.5 +45
Phase d'approche	Variable suivant le délai d'atteinte de la vitesse minimum satisfaisante	0 – 45	0 - 45
Ligne de départ	0 + Phase d'approche	45	45
Ligne d'arrivée	250 + Phase d'approche	250 + 45	250 + 45

II.2.2 Les propriétés d'intérêt du conducteur

Dans ce travail de recherche, nous manipulons deux propriétés de l'agent, i.e., les capacités d'action propre au conducteur. La première capacité d'action est relative à la vitesse maximale des véhicules conduits par les participants. Elle est notée V_{max}. Il s'agit dans un premier temps, en manipulant la vitesse maximale des conducteurs, de valider l'hypothèse selon laquelle ces derniers perçoivent intrinsèquement les possibilités d'action du véhicule conduit définies par le ratio entre les propriétés du système agent-environnement et les propriétés de l'agent (i.e., les capacités d'action) dimensionnées à partir d'unité de vitesse. Les vitesses maximales attribuées aux conducteurs sont choisies en fonction de la réglementation française en vigueur relative aux limitations de vitesse.

La seconde capacité d'action correspond à l'accélération maximale des véhicules conduits par les participants. Elle est notée A_{max}. Il s'agit cette fois-ci de vérifier si les conducteurs perçoivent intrinsèquement les possibilités d'action du véhicule conduit définies par le ratio entre les propriétés du système agent-environnement et les propriétés de l'agent (i.e., les capacités d'action) dimensionnées à partir d'unité d'accélération. Les accélérations maximales imposées aux véhicules conduits sont définies à partir de dynamiques d'accélération issues de véhicules réels modélisées par le logiciel *CarTest2000*[13].

Les quatre expérimentations vont nous permettre de répondre à ces différentes interrogations :

- *MSV* et *MSA* sont-elles des propriétés d'intérêt pour les conducteurs ?
- Les conducteurs privilégient-ils une propriété du système agent-environnement pour prendre la décision d'initier et de réguler leur dépassement automobile?
- Les conducteurs sont-ils capables d'exploiter des limites d'action distinctes durant leur dépassement ?
- Les traits de personnalité des conducteurs ont-ils une influence sur la perception et l'exploitation des *affordances* de dépassement ?

II.3 Acquisition et analyse des données expérimentales

II.3.1 Acquisition des données expérimentales

Dans les trois expérimentations, nous avons enregistré les données comportementales des participants évoluant dans un environnement virtuel à l'aide d'un logiciel propre au laboratoire : *Imagine Create & Experiment* (*ICE*)[14]. La fréquence d'acquisition des données comportementales est de 75 Hz.

Les données comportementales enregistrées comprennent toutes les actions motrices des conducteurs vers les opérateurs du simulateur de conduite durant la réalisation d'un essai : frein, accélérateur, volant, rétroviseur et boîte de vitesse – cf. expérimentation 3. Ces actions motrices sont à l'origine des comportements observés: dépassement, poursuite, renoncement ainsi que des collisions associées susceptibles de se produire dans l'environnement virtuel.

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[13] Glenn, Patrick. (2013) CarTest 2000, Automobile Acceleration Simulation Software, CarTest Software, http://www.cartestsoftware.com

[14] Logiciel de création d'objets 2D et 3D développé par Cédric Goulon (ingénieur CNRS) au sein de l'Institut des Sciences du Mouvement depuis 2001.

L'environnement virtuel est programmé à partir d'un script issu du logiciel *ICE* permettant de créer des objets virtuels 3D. Les variables à enregistrer sont également notifiées dans ce même script avec une fréquence d'acquisition à fixer. À la fin de chaque essai, le logiciel procède à l'enregistrement des données expérimentales. Les fichiers d'enregistrement ainsi obtenus sont des fichiers texte, au format «.txt », regroupant l'ensemble des variables à sauvegarder déclarées dans le script *ICE*.

II.3.2 Analyse des données expérimentales

Après l'enregistrement, les variables sont analysées à l'aide du logiciel d'analyse et de programmation de données *MATLAB*[15].

Nous modélisons chacune des données individuelles de dépassement à l'aide d'une fonction sigmoïde (Bootsma, Bakker, van Snippenberg, & Tdlohreg, 1992, p. 6), en utilisant la *Toolbox*™ Statistiques de *MATLAB*, telle que :

$$y = \frac{100}{1 + \mathrm{e}^{-k(c-x)}}$$

où *k* est un paramètre relatif à la pente de la courbe quantifiant la soudaineté de la transition d'un mode d'action vers un autre (i.e., différence juste perceptible ou seuil différentiel). Le paramètre *c* correspond, quant à lui, à la valeur critique pour laquelle 50% des situations de dépassements était jugé possible (i.e., point d'égalisation subjective ou seuil absolu). Il quantifie de ce fait le lieu de transition d'un mode d'action à un autre. Les paramètres *k* et *c* sont donc respectivement des indicateurs de l'exactitude et de la précision de la sélection d'un mode d'action.

Enfin, le paramètre *x* représente la condition expérimentale dépendant des difficultés de dépassement exprimées dans une échelle de mesure extrinsèque (i.e., valeurs de *MSV* en m/s et/ou de *MSA* en m/s²) ou intrinsèque (i.e., valeurs de *MSV*/*Vmax* et *MSA*/*Amax* en %). Le chiffre 100 indique la fréquence maximale (en %) d'apparition d'un mode d'action (e.g., doubler dans chaque essai).

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[15] Logiciel développé par la société *The MathWorks*. La version *R2011a* est utilisée lors de ce travail de recherche

Dans ce document, l'analyse de variance des comportements de dépassement est effectuée sur les moyennes du coefficient c (i.e., le point d'égalisation subjective) de chacun des conducteurs. Par ailleurs, dans l'expérimentation 2, une régression linéaire multiple à deux propriétés prédictives (MSV/V_{max} et MSA/A_{max}) est réalisée sur la moyenne des fréquences de dépassement. L'équation de la droite est du type :

$$y = a + b_1 X_1 + b_2 X_2$$

La fréquence des dépassements automobile est la variable dépendante – à prédire – (i.e., y) ; le coefficient a est l'ordonnée à l'origine ; b_1 est le coefficient de régression de la première variable indépendante – prédictive – (X_1 : MSV/V_{max}) et b_2 est le coefficient de régression de la seconde variable indépendante – prédictive – (X_2 : MSA/A_{max}). La significativité des résultats indique une relation linéaire multiple entre les comportements de dépassement (i.e., y) et les propriétés prédictives (MSV/V_{max} et MSA/A_{max}). Il conviendra alors de quantifier leurs influences respectives sur les comportements de dépassement à l'aide des coefficients de régression standardisés (b_1* et b_2*). Pour l'ensemble des analyses statistiques, le traitement est réalisé à l'aide du logiciel *STATISTICA* (version 10). Le seuil p de significativité est fixé à 0.05.

III. Chapitres Expérimentaux

III.1 Prise de décision et *affordance MSV/Vmax*

III.1.1 Résumé de l'expérimentation 1

Introduction

De nombreuses actions quotidiennes requièrent de l'individu une prise en compte de ses capacités physiques (e.g., attraper une balle avant qu'elle ne franchisse une ligne de but) pour agir avec réussite dans son environnement. Dans un contexte automobile, lorsqu'un conducteur décide d'initier un dépassement, le fait-il en considérant les limites de son véhicule ? De récentes études (Gordon & Mast, 1970; Gray & Regan, 2005) révèlent que 14% à 68% des accidents survenus lors d'un dépassement le sont au moment de son initiation, phase durant laquelle le conducteur estime la faisabilité du dépassement. Dans le cadre de cette expérimentation, nous postulons que la manœuvre de dépassement implique la perception d'*affordances*, i.e., des possibilités d'action, définies par des propriétés du système agent-environnement mises en relation avec des propriétés de l'agent. De nombreuses études ont mis en évidence la capacité des individus à percevoir des *affordances*, mais aucune étude jusqu'à présent ne s'était intéressée au dépassement automobile. Dans la continuité des travaux de Fajen concernant les tâches de freinage (e.g., Fajen, 2005a ; Fajen & Devaney, 2006) et en utilisant la formalisation mathématique de l'*affordance* établie par Warren (1984), l'expérimentation 1 questionne l'hypothèse selon laquelle un conducteur automobile désireux de doubler agirait en percevant les possibilités d'action de son véhicule. Cela suppose la perception d'une *affordance* du dépassement automobile définie par le ratio entre les propriétés relationnelles du système agent-environnement et une propriété de l'agent, i.e., les capacités d'action du conducteur. Ces deux propriétés correspondraient respectivement à la Vitesse Minimale Satisfaisante pour réussir un dépassement (*MSV*) et à la Vitesse maximale du véhicule conduit par les participants (*Vmax*). L'*affordance* de dépassement devrait ainsi renseigner les conducteurs sur la faisabilité du dépassement automobile. En d'autres termes, nous souhaitons déterminer si les conducteurs prennent la décision d'initier un dépassement en percevant une vitesse minimale satisfaisante (*MSV*) en référence à la vitesse maximale du véhicule conduit (*Vmax*).

Méthode

Afin de tester l’hypothèse selon laquelle les conducteurs percevraient une *affordance* de dépassement dimensionnée à l’action, à partir de propriétés cinématiques, nous avons constitué deux groupes, de huit conducteurs chacun. Le premier groupe possède une vitesse maximale faible (*Vmax* = 25 m/s) et le second groupe dispose, quant à lui, d’une vitesse maximale élevée (*Vmax* = 35 m/s). Dans chaque condition expérimentale proposée aux conducteurs, la difficulté du dépassement dépendait des quatorze valeurs de *MSV* calculées à partir des vitesses maximales des participants. Par ailleurs, dans chaque essai, les conducteurs possédaient une vitesse initiale égale à la *MSV* initiale (hormis pour les essais où la *MSV* initiale était supérieure à la *Vmax*). Dès lors, pour chaque condition de *MSV*, les participants du groupe avec une vitesse maximale élevée (*Vmax* = 35 m/s) devraient dépasser davantage que les participants du groupe avec une vitesse maximale faible (*Vmax* = 25 m/s).

Résultats

Des *t-test* pour groupes indépendants sont effectués sur les *PES* (i.e., Point d’Égalisation Subjective) des fréquences de dépassement individuelles, exprimées dans une échelle de mesure extrinsèque (i.e., en fonction de la *MSV*). Les courbes psychométriques confirment une plus grande propension au dépassement pour les groupes de conducteurs avec une vitesse maximale élevée. En d’autres termes, les *PES* du groupe de conducteurs avec une vitesse maximale faible sont inférieurs aux *PES* du groupe de conducteurs avec une vitesse maximale élevée. Chaque groupe de conducteurs possède ainsi des fréquences de dépassement différentes pour une même condition *MSV*.

Toutefois, des *t-test* pour groupes indépendants sont réalisés sur les *PES* des fréquences de dépassement individuelles, exprimées dans une échelle de mesure intrinsèque (i.e., en fonction de la *MSV/Vmax*). Les résultats ne permettent pas de conclure à l’existence de différences significatives entre les groupes de conducteurs. Par ailleurs, les fréquences de dépassement deviennent nulles pour les deux groupes de conducteurs lorsque la *MSV* excède la vitesse maximale de leur véhicule.

Discussion

Conformément à la théorie des *affordances* (J. J. Gibson, 1986) et à l'*affordance-based control* (Fajen, 2007a), l'ensemble des résultats obtenus met en évidence la capacité des conducteurs automobiles, durant leur dépassement automobile, à considérer les limites d'action de leur véhicule (i.e., *Vmax*). En d'autres termes, les conducteurs prennent la décision de dépasser en fonction des valeurs de l'*affordance* de dépassement *MSV/Vmax*. En ce sens, lorsque le ratio *MSV/Vmax* est inférieur à 100%, les conducteurs choisissent de dépasser. Dans le cas inverse, ils choisissent de sélectionner un autre mode d'action (i.e., poursuivre le véhicule leader ou renoncer au dépassement en cours de réalisation) jusqu'au franchissement de la ligne d'arrivée. Lors de cette étude, nous avons ainsi pu formaliser une nouvelle *affordance* et démontrer sa pertinence dans le cadre du dépassement automobile. Le cadre conceptuel des *affordances* nous a donc permis de rendre compte des processus de prise de décision des conducteurs.

Enfin, parallèlement au comportement de dépassement, nous avons pu observer des comportements de renoncement. Cette manœuvre se caractérisait dans un premier temps par l'initiation d'un dépassement puis, au cours du changement de voie, le conducteur estimait qu'il ne disposait pas de suffisamment de temps pour réussir à doubler le véhicule leader. Il décidait alors de fortement décélérer pour se rabattre derrière le véhicule leader, et ce, avant d'entrer en collision avec le véhicule obstacle. Cette capacité du conducteur à percevoir le moment opportun pour initier une manœuvre de renoncement implique de connaître très précisément les capacités de décélération de son véhicule. Dans le cadre de futures recherches, il serait ainsi intéressant de considérer la compétition entre deux *affordances* – dépassement et renoncement – afin de mieux comprendre les stratégies perceptivo-motrices en jeu lors du dépassement automobile (Marti, Morice, & Montagne, 2015) .

III.1.2 Manuscrit de l'expérimentation 1

An affordance-based approach to visually guided overtaking

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Abstract

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 Maximal Velocity of the driver's car (V_{max}). Two groups of subjects 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 car in overtaking situations constrained by fourteen 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, 2007a), our results suggest that participants select their overtaking maneuvers by perceiving an *overtake-ability* affordance.

Keywords: affordance-based control; visually guided action; driving; overtaking; virtual reality

An affordance-based approach to visually guided overtaking

Introduction

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 Inter-ministry 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 (Footnote 1), highlighting the difficulty of this task and the consequences of failure.

We identify five phases of a basic overtaking maneuver, which we describe below 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 suggest 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 head wind 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 will 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 (1979) formulation of the theory of affordances. Researchers have investigated the perception of the "*catchability*" of fly balls (Fajen, Diaz, & Cramer, 2011; Oudejans, Michaels, Bakker, & Dolné, 1996), "*avoid-ability*" of a collision by braking (Fajen & Devaney, 2006; Fajen, 2005a, 2005b, 2005c), 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, 2007a). 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: (1) *minimum satisfying velocity* (*MSV*), which we define as the minimum velocity required to overtake the lead car without colliding with the oncoming traffic, and (2) 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 on 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 the present 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 subjects' virtual car was manipulated as a between-subjects variable. The Minimum Satisfying Velocity (*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 subjects 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 (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 21. 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.). 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) 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.) linked the driver’s viewpoint in the virtual 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 rear view mirrors.

Figure 21: Overview of the set-up. Participants sat on a play seat 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.

Virtual environment

The virtual environment depicted in Figure 22 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 by a blue lighted sky with mountains, a cement-textured rectilinear two-way road (2500 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 was 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 participant's 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 (cf. see next subsection), was displayed in the upper-middle portion of the screen before each trial.

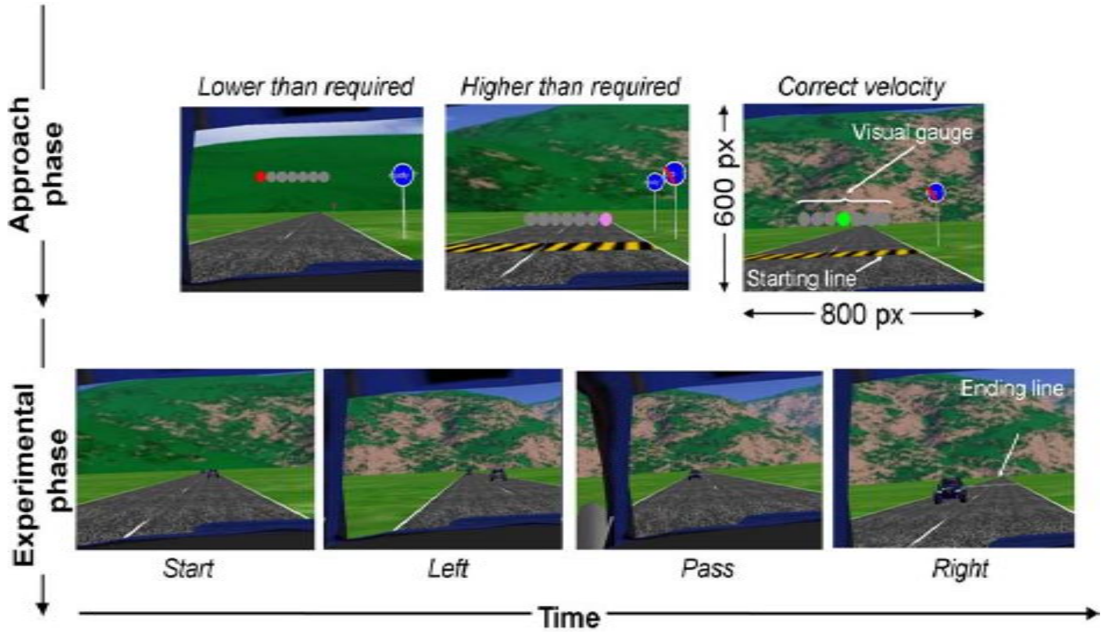

Figure 22: Screenshots of the virtual scenes during the approach (top) and the "start", "left', "pass" and "right" phases of an overtaking maneuver performed during the experimental session (bottom). During the approach phase, there was a visual gauge consisting of seven initially gray circles that changed 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.

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):

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

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 one when $V_C < V_{max}$ and zero when $V_C = V_{max}$, 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 (2):

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

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 m/s². 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 one when the car was moving and zero 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 pre-programmed 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 22). 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 participant's velocity matched with this requirement, the visual gauge disappeared, the lead and obstacle cars appeared and participant's behavior was unrestricted. Otherwise, the starting line moved 50 m further 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, the participant's 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, the participant's velocity was equal to V_{max}. Participants were also encouraged to explore the capabilities of their car, including its maximum velocity and braking, during this phase. They were asked to monitor the behavior of the surrounding cars by using the side rear view mirrors (i.e., before starting an overtake 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 car 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 one hour per participant. Short rests were given regularly according to participant's 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 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 Minimum Satisfying Velocity 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 the 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 23).

This yielded 14 $MSV^{start}/V_{\max}$ ratios ranging from 10% to 140% for the slow car and from 7.69% to 107.7% 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 the half of the MSV^{start} value. The obstacle car remained immobile on 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 them from systematically initiating an overtaking maneuver at the start of the trial without checking their rear view 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.

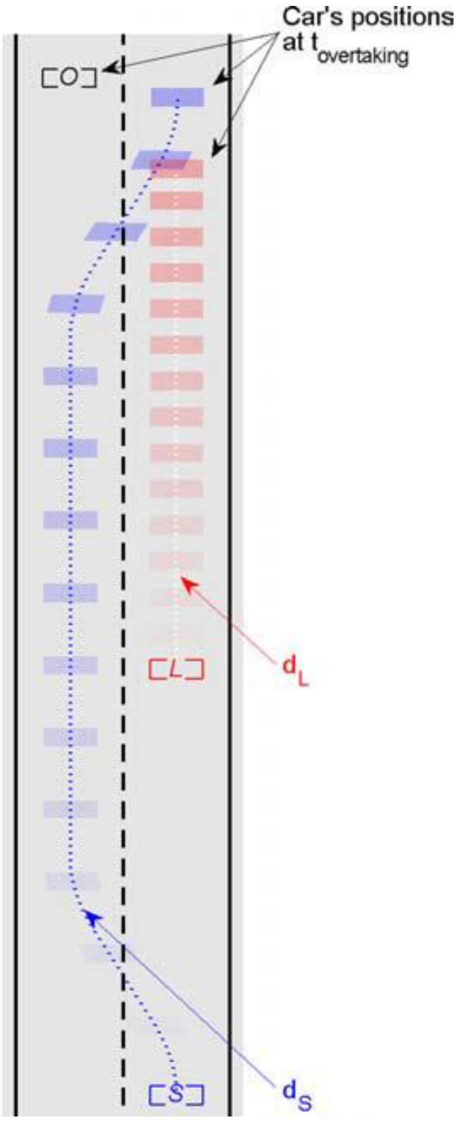

Figure 23: Numerical simulations of participant's (*S*) and lead (*L*) car's trajectories when travelling the distance d_S and d_L during the MSV^{start} condition equal to 32.5 m/s. Successive current positions of *S* and *L* cars are displayed every 40 ms while the obstacle car (*O*) remains immobile. $t_{overtaking}$ occurs when the front bumper of *S* is aligned with the front bumper of 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 $MSV^{Start}/Vmax$ ratios obtained when manipulating $Vmax$ as a between-participants variables. 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.

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

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 in introduction in the participant's car's trajectory. 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 bailout 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 on 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 Minimum Satisfying Velocity 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 $p(x)=1\Big/\left(1+\left(\frac{x}{\alpha}\right)^{\beta}\right)$ 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^2_p) and post hoc comparisons were conducted using Newman-Keuls *a posteriori* tests.

Predictions

The present 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 present 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 24 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 on the large majority of trials. In addition, collisions occurred more often during overtaking and following maneuvers (1.35% and 1.79%; left and right panels, respectively) than during bail-out maneuvers (0.27%; middle panel).

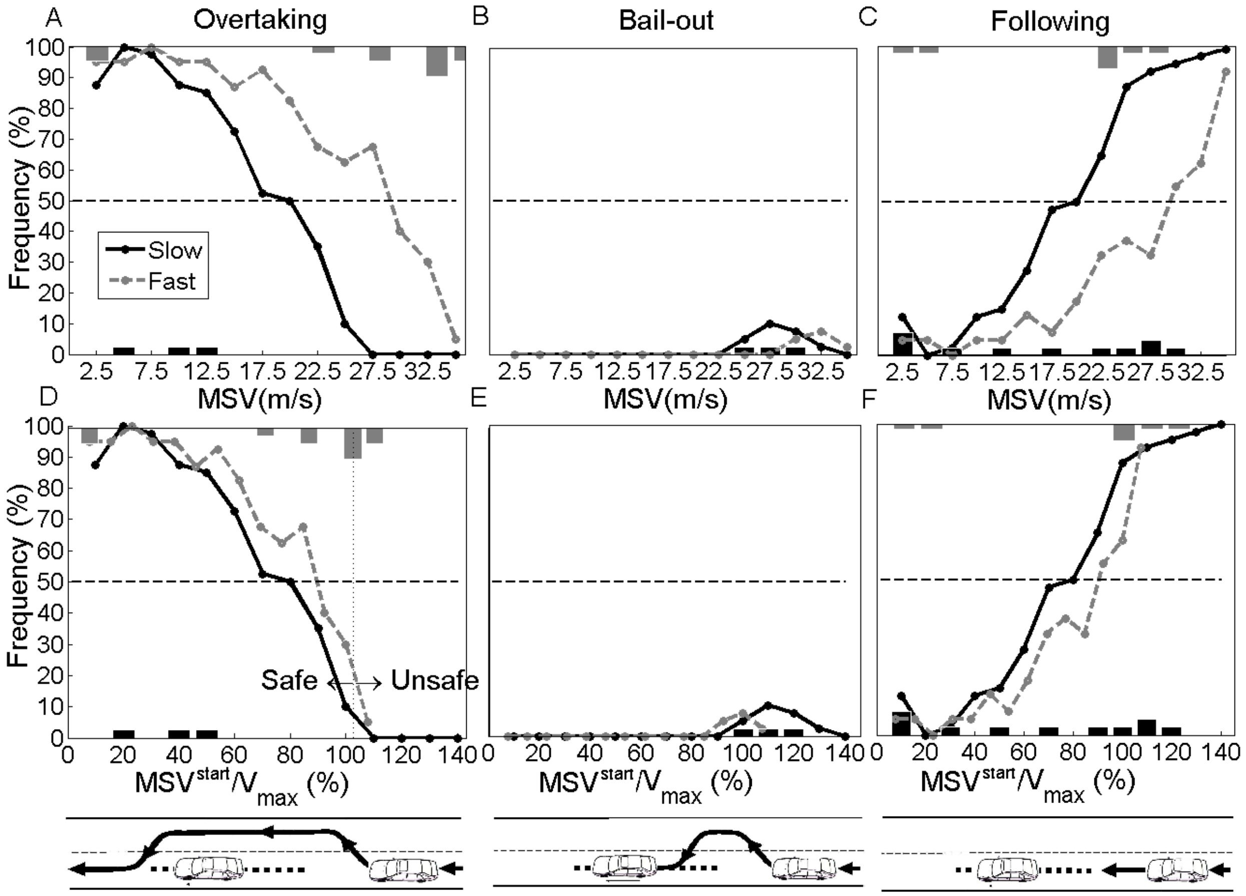

Figure 24: Average frequencies of Overtaking (A-B), Bailing out (C-D) and Following maneuvers (E-F) plotted as a function of MSV^{Start} (top) and as a function of $MSV^{Start}/Vmax$ (bottom) for the slow (plain black line) and fast cars (dotted gray line). The black histogram plotted on lower x-axis and the gray histogram plotted on the upper x-axis depict the average frequencies of collisions in each maneuver (i.e., overtaking, bailing out, following) as a function of the MSV^{Start} (top) and $MSV^{Start}/Vmax$ (bottom) for the slow and fast cars, respectively.

In order to determine whether collisions were most likely to occur when overtaking was not possible, we plotted histograms on the bottom panels of Figure 24 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 are 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 $MSV^{start}/V_{max} \leq 1$ 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 side-swiping 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 24A 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 subjects 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} ($F[13, 182] = 37.25$, $p < .05$, $\eta^2_p = .73$). The ANOVA also revealed a main effect of V_{max} ($F[1, 14] = 13.73$, $p < .05$, $\eta^2_p = .49$), confirming that subjects in the slow car group attempted significantly fewer overtaking maneuvers than subjects 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. 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 to the fast car group (*M* = 27.33 m/s; t = -3.38, df = 14, $p < .05$), confirming that subjects 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 24D depict mean frequency as a function of MSV^{start}/V_{max} for the slow and fast cars, respectively. Importantly, overtaking frequency dropped to 0% for both groups very close to the point at which MSV^{start}/V_{max} exceeded 1.0 (i.e., when the minimum velocity satisfying to successfully overtake the lead car was greater than the car's maximum velocity). This suggests that subjects 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 24D 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 subject in both groups were fitted with a logistic function to compute the *PSE* values expressed 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 group (*M* = 79.32; t = -1.09, df = 14, p>0.05).

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} /Vmax* values for the slow and fast groups. The R², α and β values provided by each individual logistic fit are also provided.

					MSV^{start}	$MSV^{start}/V_{\max}$
Group	Participants	α	β	R^2	PSE (m/s)	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

Although the PSE values were not significantly different, there does appear to be a trend toward a higher percentage of overtaking for subjects 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, subjects in the Fast group were more biased to overtake compared to subjects in the Slow group for the following reason. The overall percentage of trials in which overtaking was possible was greater for subjects in the Fast group. This is because the set of MSV^{start} values were the same for the two groups, but subjects in the Fast group could accelerate to a faster V_{max}. This may have induced a bias among subjects in the Fast group to overtake rather than follow, which could account for the small differences between the two groups in Figure 24D and Figure 24F.

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 24C and Figure 24F). Close inspection of Figure 24C and Figure 24F 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 four participants of the Fast group and three participants of the Slow group who occasionally executed bail-out maneuvers when the MSV^{start}/V_{max} ratio was close to 100% (see Figure 24B and Figure 24E).

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 25 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 25; see also the A vignette on the upper panel of Figure 25 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.

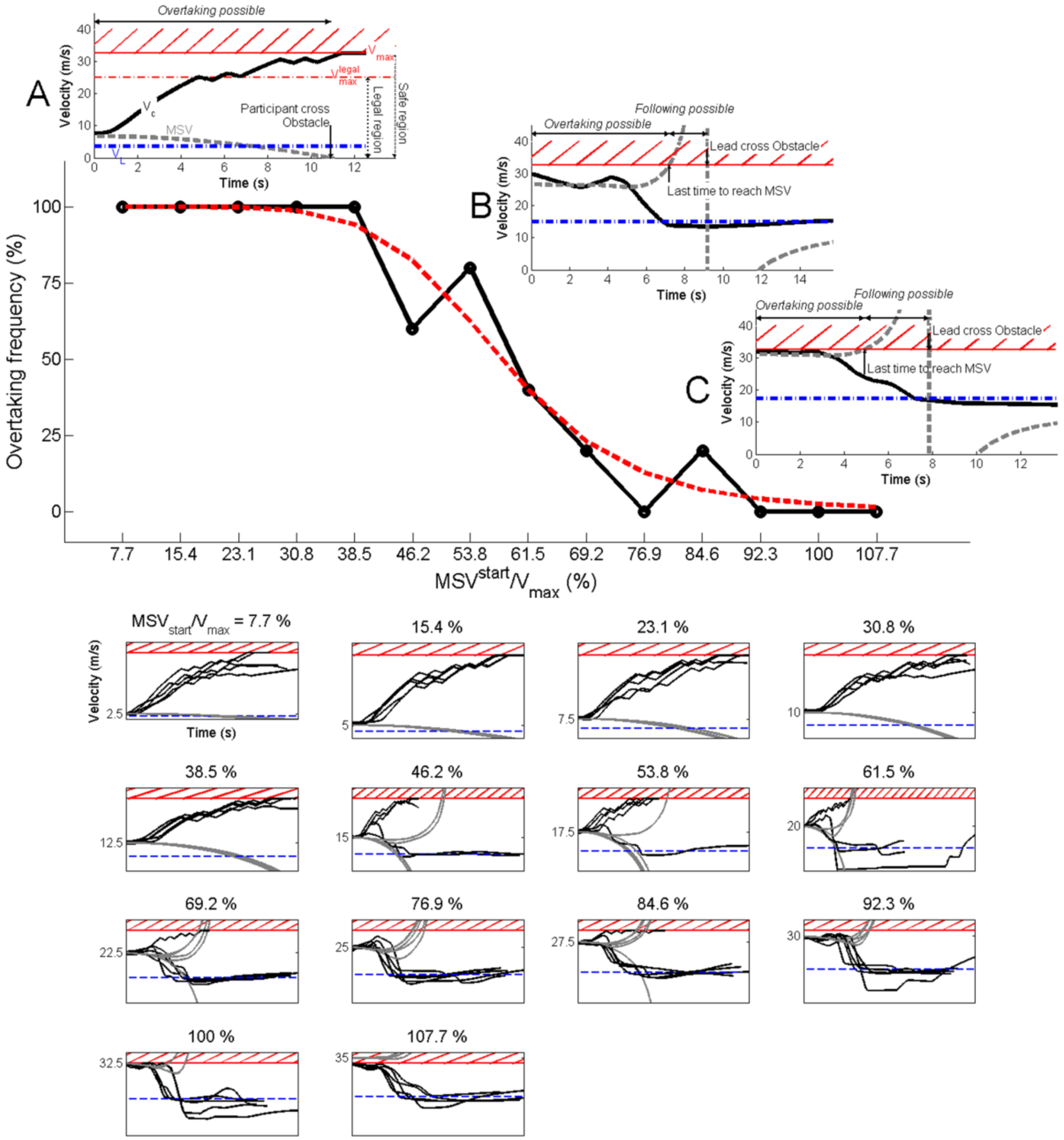

Figure 25: Typical individual set of overtaking frequencies monitored with participant ID number 8 over the five repetitions of each condition. On the upper panel, the sigmoid curve (dotted line) depicts the individual fit of overtaking frequencies by a logistic function, plotted as a function of the MSV^{Start}/V_{max} ratios with the point of subjective equality (*PSE*). 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 cross the level of the obstacle car). Horizontal arrows indicate the possible action modes (e.g., overtaking and following maneuvers). On 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 5 repetitions of each MSV^{Start}/V_{max} ratio.

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 5 vignettes in the lower panel of Figure 25; see also the C vignette on the upper panel of Figure 25). 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 non-existent. 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 25. 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 on the upper panel of Figure 25 shows an example of such a trial, which we classified as a bail out.

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 26). 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, the participant's mean speed on unsafe trials (designated by the star symbols in Figure 26) 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 Stop 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.

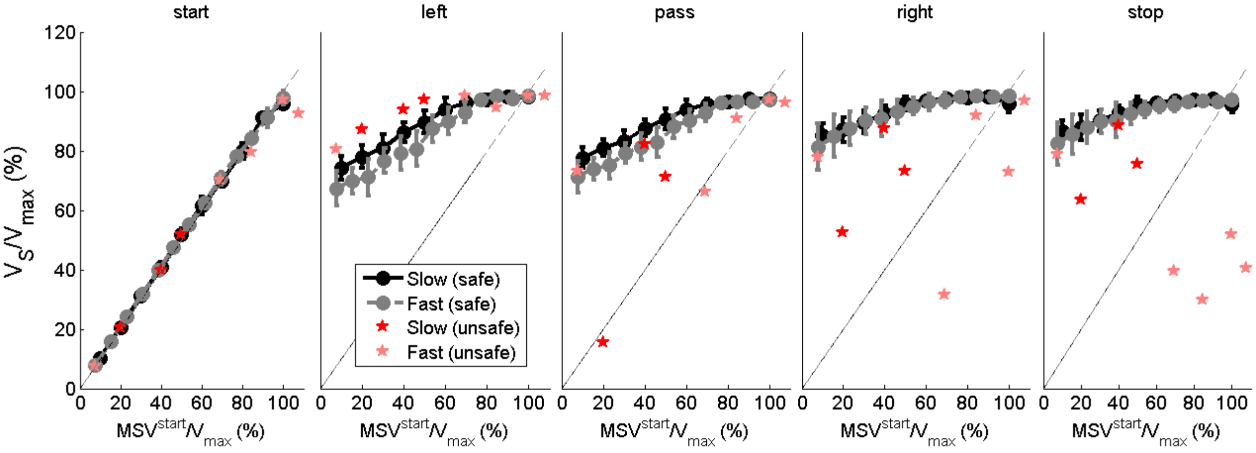

Figure 26: Average ratio between the participant's velocity over the participant's maximum velocity ($V_S/Vmax$) plotted as a function of the $MSV^{Start}/Vmax$ conditions during the five successive phases of the overtaking maneuver. Values are computed during safe (● symbols) and unsafe overtaking maneuvers (★symbols) with dark and light colors for the slow and fast cars, respectively. Vertical bars depict the standard deviation of individual mean.

Discussion

The objective of this study was to investigate the perceptual-motor processes underlying visually guided overtaking maneuvers. We hypothesized that 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., $MSV^{start}/V_{max} > 1$) 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 to 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, following, or bailout) 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}. Bailouts were infrequent. Furthermore, although subjects in the fast car group were more likely to overtake than subjects 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 24D). This could reflect a minor difference between the *MSV* that we calculated for the purposes of our analyses and the *MSV* that subjects 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 non-risky way) was equal to 100%.

Additional issues

Lastly, we consider two theoretically significant issues that were not directly addressed by the present 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 car on the basis of the present study. However, previous studies have demonstrated that humans are capable of perceiving affordances in other contexts when the dimensions of their body 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 bail-outs 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' behaviour during overtaking may be possible by considering overtaking in terms of a competition between two affordances (Marti, Morice & Montagne, 2015).

Conclusions

In conclusion, the findings of the present 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.

Footnotes

(1) French Inter-ministerial Observatory of Road Safety, Road traffic accidents involving Injuries of: collection of raw data, ONISR, May 2013, p. 69

Acknowledgments

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