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HEC MONTRÉAL

Évaluation d'une contre-mesure physiologique pour contrer la distraction visuelle au volant : Comparer les effets d'alertes multimodales sur l'attention visuelle des conducteurs

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Résumé

L'utilisation de cellulaire au volant est un phénomène dangereux et connu en matière de sécurité routière. Cependant, la présence de nouvelles technologies dans les voitures, tels les systèmes d'infodivertissement embarqué (SIE), est peu connue, mais tout aussi dangereuse. L'interaction avec ces systèmes est complexe et demande une attention visuelle élevé de la part des conducteurs, ce qui handicape lourdement l'attention visuelle que ces derniers accordent à la conduite sécuritaire. Ce mémoire par articles propose de concevoir et d'évaluer une contre-mesure qui permettrait, à l'aide de l'oculométrie, de calculer l'état attentionnel en temps réel du conducteur afin de l'alerter lorsque son regard hors route dépasse un seuil critique.

Pour ce faire, deux expérimentations ont été réalisées. La première fut menée auprès de 21 participants qui ont réalisé trois conditions expérimentales (première et seconde conduite avec la contre-mesure et une condition de contrôle où ils conduisent sans). Lors de cette étude, les participants devaient interagir avec un SIE en même temps qu'ils conduisaient et recevaient une alerte auditive tactile lorsque ces derniers passaient trop de temps à regarder le SIE. Pour la seconde expérimentation, 36 participants ont été soumis aux mêmes interactions et conditions expérimentales que pour la première expérimentation, mais cette fois-ci, ils étaient répartis en trois groupes distincts selon le type d'alerte qu'ils recevaient de la contre-mesure (auditive-visuel, tactile-visuel et auditive-tactile-visuel).

Les résultats de la première expérimentation montrent que la contre-mesure proposée est efficace à rediriger l'attention visuelle des conducteurs sur la route et qu'elle améliore les performances de conduite lors d'interactions avec un SIE. Les résultats de la deuxième expérimentation, quant à eux, indiquent un temps de réaction plus lent pour les alertes incluant la modalité visuelle. De plus, il a été constaté lorsque les participants conduisaient avec la contre-mesure une seconde fois, ceux-ci tentaient d'en prévenir le déclenchement, plutôt que d'y réagir.

Les contributions de ce mémoire passent par l'efficacité de la contre-mesure proposée à accomplir son rôle. Ces résultats suggèrent de nouvelles pistes de solution afin de répondre à la problématique de la distraction au volant, mais aussi à inspirer les concepteurs sur les effets des SIE au volant. Cette étude démontre également le potentiel lié à l'intégration d'oculométrie au sein de voiture en matière de sécurité routière.

Mots clés : Contre-mesure · Distraction · Modalités sensorielles · Conscience de situation · Sécurité routière · Prévention d'accidents · Système d'infodivertissement embarqué · Haptique · Simulateur de conduite

Méthodes de recherche : Simulateur de conduite · Collecte expérimental · Oculométrie

Abstract

The use of cellphones while driving is a dangerous and well-know phenomenon in term of road safety. However, the presence of new technologies in cars, such as In-Vehicle Infotainment Systems (IVIS) is less known, but equally dangerous. Interacting with these systems is complex and requires from the drivers a high visual attention, which significantly impairs the visual attention needed for safe driving. This article-based thesis proposes to design and evaluate a countermeasure that takes into account driver's attentional state in real-time through eye-tracking to alert them when their off-road gaze exceed a critical threshold in order to redirect it back to the road.

To do so, two experiments were conducted. The first involved 21 participants who experienced three experimental conditions (first and second time driving with the countermeasure and a control condition where they drove with no countermeasure). In this study, participants had to interact with an IVIS while driving and received auditory-tactile alerts when they spent too much time looking at the IVIS. For the second experiment, 36 participants underwent the same interactions and experimental conditions as in the first experiment, but this time they were divided into three distinct groups based on the type of alert they received from the countermeasure (auditory-visual, tactile-visual, auditory-tactile-visual).

The results of the first experiments demonstrate that the proposed countermeasure is effective in redirecting driver's visual attention to the road and in improving driver's driving performance during an interaction with an IVIS. For the second experiment, results show slower reaction times for alerts that included the visual modality. Additionally, it as observed that when participants were driving with the countermeasure a second time, they attempted to prevent its triggering rather than reacting to it.

The contribution of this thesis lies in the effectiveness of the proposed countermeasure. These results suggest a new avenue to address the issue of driving distraction and can also inspire designer regarding the effects of IVIS while driving. Furthermore, this study demonstrates the potential of integrating eye-tracking within cars in terms of road safety.

Keywords: Countermeasure · Distraction · Sensory modalities · Situation Awareness · Road Safety · Accident Prevention · In-Vehicle Infotainment Systems · Haptic feedback · Driving Simulator

Research methods: Driving simulator · Experimental data collection · Eye-tracking

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CS : Conscience de situation

SA : Situation Awareness

SAC : Système d'aide à la conduite

ADAS : Advance Driver Monitoring Systems

SIE : Système d'infodivertissement embarqué

IVIS : In-vehicle infotainment systems

SSEC : Système de surveillance de l'état du conducteur

DMS : Driver Monitoring Systems

Avant-propos

Ce mémoire par article a été écrit avec l'approbation de la direction administrative du programme de M. Sc. en gestion, spécialisation expérience utilisateur de HEC Montréal. Les co-auteurs impliqués dans la rédaction de l'article inclus dans ce mémoire ont donné leur consentement pour son inclusion dans ce document.

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L'article scientifique présenté au chapitre 2 de ce mémoire sera soumis au journal *Human Computer Studies*.

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Introduction

La conduite est une activité qui demande une grande quantité d'attention aux conducteurs afin de pouvoir naviguer dans l'environnement dynamique qu'est la route. Pour cette raison, la distraction au volant représente un facteur important parmi les causes d'accidents en voiture et de ce fait, est un enjeu important en matière de sécurité routière. Dans la dernière décennie, un nombre grandissant d'accidents sur la route s'est vu associé à ce phénomène. Selon la définition utilisée ou du type d'étude réalisée, les chiffres varient entre 5 % à 25 % de la totalité des accidents en Europe (Hurts et al., 2011), représentent 25,3 % de la totalité des morts sur la route au Canada en 2017 (Brown et al., 2021) et 8,74 personnes par jours aux États-Unis (Stewart, 2022). Il est actuellement difficile de déterminer l'ampleur des implications de la distraction volant pour plusieurs raisons. Tout d'abord, les rapports d'accidents ne comptabilisent pas la distraction comme étant la cause des accidents. Ensuite, les conducteurs n'admettent pas toujours avoir été distraits au moment de l'accident. Cependant, une étude utilisant des données récoltées sur la conduite en conditions naturelles a permis d'identifier à l'aide de caméras vidéo et de senseurs que l'impact de la distraction sur 905 accidents était de 68,3 % (Dingus et al., 2016). Dans cette étude, les auteurs mettent en évidence que plus de la moitié de ces accidents (51,93 %) sont liées aux conducteurs engagés dans des activités distrayantes qui ne sont pas en lien avec la conduite, montrant ainsi que la distraction au volant est un phénomène important et sous-représenté dans les statistiques en sécurité routière.

Malgré une baisse remarquée du nombre d'accidents fatale au Canada depuis 2008, la proportion d'accidents liés aux distractions est quant à elle en augmentation (Brown et al., 2021). Ce phénomène est principalement dû à la présence grandissante des technologies dans les voitures qui amène un changement à nos interactions avec celles-ci. Auparavant, les interactions étaient soumises au jugement du conducteur qui pouvait identifier le moment opportun pour interagir selon sa capacité à pouvoir réaliser une tâche non essentielle à la conduite. Par exemple, les fonctionnalités disponibles se limitent généralement à la lecture de contenu audio. Cependant, avec la présence croissante de la technologie dans les véhicules, cette relation tend à s'inverser. Le conducteur ressent une pression d’agir et peut décider d’interagir à un moment où il n’est pas en mesure d’effectuer une tâche non essentielle à la conduite. Par exemple, un conducteur peut maintenant recevoir des messages durant la conduite et peut être tenté de les lire tout en conduisant. Une technologie particulièrement problématique durant la conduite est les systèmes d’infodivertissement embarqué (SIE)[1].

Les SIE sont des systèmes électroniques qui offrent des fonctionnalités de divertissement aux conducteurs tels que d'écouter des contenus auditifs, visionner des films, communiquer, accéder à internet, écouter ses courriels, ainsi que d’autres fonctions qui ne sont pas essentielles à la conduite d’un véhicule. Cependant, ces systèmes offrent aussi des fonctionnalités pratiques qui facilitent la conduite, par exemple en fournissant des informations sur la navigation en temps réel, assistance pour le stationnement ainsi qu’en affichant des systèmes d’aide à la conduite comme les alertes de changement de voie et de dépassement de la limite de vitesse. Des exemples communs de SIE comprennent l’affichage du tableau de bord, les interfaces à écran tactile et les commandes vocales.

Figure 1: *Conducteur interagissant avec un SIE*

Note. Tiré de «Toyota introduces Apple CarPlay/Android Auto on select vehicles », 1 novembre 2019, Downtown Toyota

Interagir avec un SIE impose aux conducteurs de diriger leur attention visuelle vers l’écran intégré au tableau de bord, détournant ainsi leur attention de la route. Cette transposition d'attention entre une tâche liée à la conduite à une tâche non liée à la conduite est associée à une dégradation des performances de conduites associées à un temps de réaction plus lent aux situations dangereuses (Strayer et al., 2017), une décélération de la vitesse de conduite (Platten et al., 2013), ainsi qu'à une augmentation des déviations latérales et longitudinales des voies de circulations (Ramnath et al., 2020). Dans un rapport sur les effets de l'interaction avec des SIE durant la conduite sur les performances de conduites, Ramnath et al. (2020) indiquent que de nombreuses fonctions offertes par les SIE ne devraient pas être disponibles durant la conduite en raison de leur nature distrayante. Malgré le fait que ces systèmes soient conçus pour optimiser le traitement des informations par le conducteur (Platten et al., 2013), plusieurs études ont révélé que l'interaction avec les SIE pendant la conduite nuit considérablement à l'attention visuelle sur la route et à la performance de conduite (Blanco et al., 2006; Reyes & Lee, 2004; Strayer et al., 2019).

Les recherches existantes indiquent que l'industrie du transport est consciente des conséquences générées par les SIE. En réponse, des directives pour faciliter le traitement d'information des SIE lors de leur utilisation ont été élaborées pour guider les fabricants dans la conception d'interfaces moins distrayantes (Commission of the European Communities, 2008; Driver Focus-Telematics Working Group and others, 2003). Toutefois, même avec ces recommandations en place, la National Highway Traffic Safety Administrator (NHTSA) a identifié que plusieurs des fonctionnalités offertes par ces systèmes sont considérées comme étant trop distrayantes pour les conducteurs afin d'être utilisée pendant la conduite (National Highway Traffic Safety Administration, 2013). Cependant, une étude a démontré que les effets des SIE sur les performances de conduites et le comportement du regard ne respectaient pas les standards lors d'interactions manuelles (Ramnath et al., 2020). D'autres études ont aussi constaté que l'interaction physique et vocale avec ces appareils augmente le temps de réaction du conducteur de 45.9% et 26.5% respectivement (Burns et al., 2002), une augmentation qui est plus grande que la conduite sous l'influence de l'alcool (12.4%) (Burns et al., 2002) ou du cannabis (21%) (Sexton et al., 2000).

Utiliser un SIE en conduisant présente des similitudes avec l'utilisation de téléphone intelligent en matière d'interactions (écran tactile et contrôle vocal), mais aussi avec les fonctionnalités (navigation, consommer du contenu auditif et communiquer). Cependant, à cause de leurs conséquences négatives sur la sécurité routière, manipuler un téléphone intelligent pendant la conduite est légalement interdit dans de nombreux pays (World Health Organization, 2018). Au Canada, l'utilisation de téléphone intelligent est légalement proscrite dans toutes les provinces canadiennes depuis 2008 et au Québec la loi va plus loin et interdit l'usage d'écran d'affichage pour tout informations qui ne sont pas utile à la conduite (SAAQ, 2023). D'autres mesures ont aussi été misent au point par les fabricants de téléphones intelligents qui ont conçu un « mode conduite » qui restreint les fonctions de l'appareil lors de la conduite, limitant les interactions vocales pour les fonctions d'envoi de message, appelé et contrôlé les médias (*Get started with Google Assistant driving mode - Google Assistant Help*, 2023; *Use the Driving Focus on Your iPhone to Concentrate on the Road*, 2022). En revanche, il n'existe actuellement très peu de mesure commercialisée ou facilement accessible qui soit explicitement conçue pour atténuer les distractions induites par les SIE, qui posent aussi un problème sérieux pour la sécurité routière.

Des contre-mesures (mesures proactives visant à prévenir et réduire les risques de sécurité liés au comportement des utilisateurs) existent pour assister les conducteurs dans leur tâche primaire qu'est la conduite sécuritaire comme les systèmes d'aide à la conduite (SAC). Ces systèmes sont conçus pour soutenir activement les conducteurs à opérer leur véhicule de manière sécuritaire en réagissant à leurs erreurs (ex : prévention de collision, avertisseur de sortie de voie ou la surveillance d'angle mort (Marchau et al., 2005). Cependant, il est essentiel de noter que les SAC réagissent principalement aux erreurs engendrées par la distraction plutôt que de les anticiper de manière préventive. Par ailleurs, les systèmes de surveillance de l'état du conducteur (SSEC) évaluent l'état cognitif du conducteur pour le prévenir lorsque le système détecte de la somnolence, de la distraction ou du stress afin d'en réduire les risques liés à ces états (Hayley et al., 2021). Toutefois, ces systèmes de surveillance se limitent à déclencher des alertes sans mettre en œuvre des mesures proactives en réponse à l'évaluation de l'état du conducteur. Bien que les SAC et les SSEC soient des systèmes éprouvés qui améliorent la sécurité routière

(Hayley et al., 2021; Masello et al., 2022), elles ne constituent pas une solution complète pour prévenir de manière préventive les distractions liées aux SIE.

1. Objectifs

Afin de prévenir les distractions causées par les SIE lors de la conduite, ce mémoire propose une contre-mesure technologique qui utilise des données physiologiques pour capturer l'attention visuelle du conducteur à l'aide d'un oculomètre. Les contre-mesures technologiques sont un type de contre-mesure qui prend la forme de système et d'interface afin de limiter ou assister un conducteur durant la conduite, par exemple les systèmes de surveillance de l'état du conducteur (SSEC) et les systèmes d'aide à la conduite (SAC). L'objectif de la contre-mesure proposé dans ce mémoire est d'alerter le conducteur lorsque son regard se détourne de la route pendant plus de 1,6 seconde afin de rediriger son attention visuelle sur la route. Le choix d'utiliser un seuil de 1,6 seconde est fondé sur les résultats de Horrey & Wickens (2007) qui ont démontré que 86% des accidents sont arrivés lorsque le regard des conducteurs dépassait ce seuil.

L'objectif premier de ce mémoire est d'évaluer empiriquement l'efficacité d'une contre-mesure dans son rôle à augmenter l'attention visuelle d'un conducteur sur la route pendant ses interactions avec un SIE dans un contexte de conduite en simulateur. En augmentant l'attention visuelle sur la route, l'intention est de rendre le conducteur plus alerte à son environnement de conduite, lui permettant ainsi d'avoir de meilleures performances de conduites et de prévenir de potentiels accidents. De ce fait, la première question de recherche est :

Q1: Dans quelle mesure une contre-mesure qui prend en considération le regard d'un conducteur est-elle efficace à rediriger l'attention visuelle d'un conducteur d'un SIE à la route ?

Si cette contre-mesure est efficace, un nouveau champ d'investigation s'ouvre : comment la contre-mesure peut-elle alerter les conducteurs de manière plus efficace? Afin d'avertir les conducteurs, les SAC utilisent des modalités d'alerte auditive et visuelle. Cependant, d'autres recherches récentes ont également indiqué que la modalité tactile est prometteuse pour améliorer l'efficacité des alertes dans un contexte de conduite (Baldwin & Lewis, 2014; Ho et al., 2005a, 2006; Sklar & Sarter, 1999; J. J. Young et al., 2003). De plus, des recherches ont démontré que les combinaisons bimodales améliorent le temps de réaction (Diederich & Colonius, 2004; van Erp et al., 2015). Cependant, l'impact de cette amélioration dans un contexte de conduite n'est pas encore clair pour la combinaison trimodale. Afin d'examiner cette question dans le contexte de la conduite avec la contre-mesure proposée, la deuxième question de recherche de ce mémoire est :

Q2: Laquelle des combinaisons entre les modalités auditive, tactile et visuelle est la plus efficace pour rediriger l'attention visuelle d'un conducteur d'un SIE à la route ?

Pour répondre à ces questions, deux expérimentations ont été réalisées. Pour répondre à la première question, 21 participants ont conduit avec et sans la contre-mesure dans un simulateur de conduite. Pendant cette expérimentation, ceux-ci devaient interagir avec un SIE tout en conduisant et recevaient des alertes auditive-tactile lorsque leur attention visuelle n'était plus dirigée sur la route après 1,6 seconde. Pour répondre à la deuxième question de recherche, 36 participants ont réalisé le même protocole que lors de la première expérimentation. Cependant, ces participants ont été aléatoirement divisés en 3 groupes ayant chacun une combinaison de modalité différente pour les alerter soit : audio-visuel, tactile-visuel et auditive-tactile-visuel.

2. Structure du mémoire

Ce mémoire avec article se compose de deux expérimentations présentées dans un même article. Une première collecte de données s'est déroulée en été 2022 avec 21 participants. Les données collectées ont été utilisées pour la première expérimentation qui visait à répondre à la première question de recherche. Lors de celle-ci, la combinaison de modalités pour l'alerte a été auditive-tactile. Pour la seconde collecte de données, celle-ci s'est déroulée en automne 2022 avec 51 participants. Les données collectées ont été quant à elle utilisées pour la deuxième expérimentation qui visait à répondre à la deuxième question de recherche. Suite à la première expérimentation, un article a été écrit afin d'être soumis à CHI 2023 (Annexe A). Malheureusement, cet article n'a pas été retenu, mais plusieurs commentaires constructifs et pertinents ont été émis par les réviseurs. Ces derniers ont été pris en compte et intégré dans un second article qui est présenté au chapitre 2 de ce mémoire. Cet article, comprenant les deux expérimentations a été rédigé pour être soumis au Journal of Human-Computer Studies.

3. Contributions

Les collectes de données présentes dans ce mémoire ont été réalisées au sein du Tech3Lab de HEC Montréal. De ce fait, le travail derrière ce mémoire s'est vu réalisé en collaboration avec l'équipe du laboratoire. Le tableau ci-dessous présente en pourcentage ma contribution ainsi que celles des membres que l'équipe du Tech3Lab a chacune des étapes de mon processus.

Table 1: *Contributions aux responsabilités du projet de recherche*

Étapes du processus	**Contributions**
Définition des questions de recherche	Développement des questions de recherche – 70% 1. Les questions de recherche ont été formulées avec l'aide de mes co-directeurs : Pierre-Majorique Léger et Anne-Frances Cameroun, mais aussi Zoubeir Tkiouat (doctorant) et Sylvain Sénécal.
Revue de littérature	Recherche et lecture d'articles scientifiques liés à ma recherche – 90% Rédaction de la revue de littérature – 100%

Conception de la contre-mesure	Rechercher les propriétés des alertes – 100% Concevoir la contre-mesure – 80% • La conception, la fabrication et les tests de la contre-mesure ont été entièrement réalisé par moi. • La programmation du code derrière la contre-mesure a été réalisé par Zoubeir Tikouat (doctorant). • La housse recouvrant le siège vibro-tactile à été réalisé par une couturière.
Conception du design expérimental	Formuler une déclaration auprès du CER – 90% • J'ai rempli les formulaires requis pour obtenir une approbation du CER pour réaliser mon étude. • L'équipe du Tech3Lab a révisé le document pour s'assurer que la demande soit complétée adéquatement Conception du protocole expérimentale – 90% • Je me suis basé sur les protocoles expérimentales précédents du Tech3Lab afin de bien représenter ce dernier lors de l'accueil et le départ des participants. • Le protocole à également été révisé par l'équipe du Tech3Lab avant le début de la collecte de connées. Installation de la salle de collecte – 70% • L'installation et la calibration de l'oculomètre a été réalisé par moi et Zoubeir Tikouat. • J'ai installé la contre-mesure sur le simulateur • Le simulateur automobile et les ordinateurs pour la collecte de données ont été installé par l'équipe du Tech3Lab. Réalisation des pré-tests – 90% • J'ai réalisé tous mes pré-tests avec l'aide de participants que j'ai recruté. • J'ai présenté mes pré-testes devant mes co-directeurs Pierre-Majorique Léger et Ann-Frances Camron, lesquelles m'ont données des commentaires et leur approbation pour commencer la collecte.

Recrutement des participants	Déterminations des critères et conditions de recrutement des participants – 100% Recrutement des participants – 90% • Pour ma première étude j'ai personnellement recruté des participants. • Pour ma seconde étude j'ai recruté des participants grâce au panel de HEC Gestions des participants – 90% • J'ai assuré les communications auprès de participants avant et après l'expérimentation. • Le suivi des compensations a été réalisé par l'équipe du Tech3Lab.
Collecte de données	Réalisation des collectes de données – 90% • J'ai réalisé ma première collecte de données seul. • Pour ma seconde collecte de données j'ai eu l'aide des assistants.es de recherches du Tech3Lab pour réaliser la modération pendant l'expérimentation.
Analyse des données	Extraction et nettoyage des données – 100% • Préparation des données pour les analyses statistiques. Analyse des données – 70% • J'ai eu l'aide de Zoubeir Tikouat (doctorant) pour réaliser les tests statistiques.

Écriture	Écriture de mon premier article – 100% • J’ai eu des commentaires constructifs de la part de mes deux co-directeurs afin d’améliorer la qualité de mon article, mais aussi pour assurer que tous les sujets nécessaires ont été abordés. Écriture de mon second article – 100% • J’ai eu des commentaires constructifs de la part de mes deux co-directeurs afin d’améliorer la qualité de mon article, mais aussi pour assurer que tous les sujets nécessaires ont été abordés. • J’ai aussi utilisé les commentaires que j’ai reçus lors de la soumission de mon premier article à la conférence CHI afin de bonifier mon second article.

Chapitre 1: Revue de la littérature

Cette revue de la littérature vise à faire la synthèse de l'état actuel de la recherche en lien avec les thèmes abordés dans ce mémoire. Celle-ci débute en fournissant une définition de la conscience de situation et en expliquant son rôle dans le processus de prise de décision et d'acquisition de l'information au sein d'un système dynamique et complexe. Elle établit par la suite le concept de distraction au volant et établit un lien entre celui-ci et la conscience de situation à travers l'attention visuelle portée à la route. De plus, cette revue de la littérature va aussi examiner une variété d'études empiriques portant sur les modalités sensorielles employées dans les automobiles pour alerter les conducteurs. Les effets des différentes combinaisons de ces modalités, notamment les combinaisons bimodales et trimodales, sont également abordés et analysés. Enfin, les solutions visant à atténuer la distraction au volant sont présentées. La littérature scientifique ainsi que l'état actuel du marché automobile sont examinées pour les SSEC et les SAC, et leurs limites identifiées. Cette revue de la littérature se conclut en présentant une contre-mesure contextuelle qui vise à rediriger l'attention visuelle du conducteur vers la route lorsqu'il est visuellement distrait. Ces limites et lacunes seront aussi discuté, soulevant ainsi les écarts dans la littérature et le marché automobile.

Une première recherche dans la littérature académique a été réalisée dans le moteur de recherche de *Google Scholar* afin de me familiariser avec les construits entourant les sujets abordés dans ce mémoire. Suite à celle-ci, les mots clés et construits suivant ont pu être identifié; *countermeasure, driver distraction, in-vehicle infotainement systems, situational awareness, visual attention, context-sensitive, driving* et *alerts*. Ces derniers ont été jumelés afin d'en ressortir des articles pertinents dans les moteurs de recherche *Google Scholar*, *Web of Science*, *ACM Digital Library* et *IEEE Xplore*.

D'autres articles et documentations scientifiques ont été trouvé en utilisant les citations de références jugées importantes et pertinentes à la réalisation de ce mémoire. Ainsi, le *foward citation* a été utilisé pour les références avec des fondements théoriques comme la conscience de situation et la distraction au volant, alors que le *backward citation* a été utilisé principalement pour les références sur les effets des combinaisons des modalités sensorielles afin de couvrir l'ensemble de la littérature.

Keyword : Contre-mesure, Système d'infodivertissement embarqué, Conscience de situation, Distraction, Modalités sensorielles, Simulateur de conduite, Sécurité routière.

1. La conscience de situation

La conscience de situation est une compétence critique pour un opérateur humain qui implique de garder en mémoire un grand nombre d'informations provenant de diverses sources au fil du temps ainsi que l'organisation et l'interprétation de ces informations (Howell, 1993). Tout d'abord abordé en aviation comme moyen d'améliorer la performance des pilotes et réduire les risques d'accident, ce construit est maintenant appliqué au large domaine du facteur humain, incluant les opérations de système large et complexe (ex. : usine et centrale énergétique), l'élaboration de stratégie tactique (ex. opérations d'urgences, policière et militaire) ainsi que dans notre quotidien (ex. conduire une voiture et marcher). Étant donné que ces environnements dynamiques sont en constantes évolutions, souvent de manière complexe, une grande partie, du travail de l'opérateur derrière ces systèmes consiste à acquérir et maintenir une CS (M. R. Endsley, 1995). Même si avec l'expérience ceux-ci sont en mesure d'acquérir et maintenir plus facilement une meilleure CS (Randel et al., 1996), il n'en reste néanmoins qu'avec les progrès rapides dans les systèmes d'information, le défi auxquels ces opérateurs font face n'ai plus acquérir l'information, mais de la filtrer pour acquérir l'information importante en lien avec l'objectif de l'opérateur (M. Endsley, 2001).

La définition la plus utilisée pour le construit de la CS est : « la perception des éléments de l'environnement dans le temps et l'espace, la compréhension de leur signification et la projection de leur état dans un futur proche » [traduction libre] (Endsley, 1988, p.97). Alors que la CS fait référence à un état de connaissance, le processus par lequel un individu acquiert celui-ci est l'évaluation de la situation (M. R. Endsley, 1995). Dans sa définition, M. Endsley (1995) décompose ce processus pour acquérir une CS, l'évaluation de situation, en trois niveaux hiérarchiques distincts.

Le niveau 1 : la perception des éléments dans l'environnement consiste à percevoir le statut, les attributs et la dynamique des éléments pertinents présents dans l'environnement. Par exemple, un automobiliste doit être au courant des informations suivantes : la position, la vitesse et la direction de son véhicule ainsi que des autres éléments présents dans son environnement (ex. autres véhicules, piétons, signalisation, obstacles, climat, etc.).

Le niveau 2 : la compréhension de l'environnement donne un sens aux éléments perçus au niveau 1. À ce niveau, l'opérateur humain crée des associations entre les éléments et les compare à des modèles mentaux que celui-ci a accumulés grâce à l'expérience. À la différence du niveau 1 ou un opérateur novice est capable de la même qualité d'analyse qu'un opérateur expérimenté, le novice peut avoir plus de difficulté à réaliser des liens entre les différents éléments alors que l'expert sera plus rapide à réaliser ces liens ainsi que d'être en mesure d'identifier plus de modèles. Pour reprendre l'exemple de l'automobiliste, la compréhension des éléments de son environnement se traduit par l'interprétation que la route peut être glissante ou bien que le conducteur soit dans une zone scolaire ou de construction, raisons pour lesquelles celui-ci doit adapter sa conduite.

Finalement, le niveau 3 : la projection de l'état futur est l'habilité de l'opérateur à projeter l'évolution futures des éléments de l'environnement dans un court terme. La connaissance requise pour atteindre ce niveau passe par la combinaison du niveau 1 : la perception et du niveau 2 : la compréhension. Ce niveau permet entre autres de prédire les différentes actions et événements possibles dans l'environnement. Par exemple, un conducteur automobile doit être en mesure de prédire de possible collision afin de pouvoir prendre les actions requises pour l'éviter.

Le construit de la CS est étroitement lié à la prise de décision. En effet, afin de prendre des décisions appropriées, il est nécessaire de procéder à une évaluation précise de la situation (Wellens, 1993). Par exemple, lorsqu'un opérateur à un haut niveau de CS, celui-ci peut percevoir (niveau 1), comprendre (niveau 2) et projeter (niveau 3) l'information disponible dans son environnement de manière précise et en temps voulu. Une fois l'évaluation de la situation établie, ce dernier peut utiliser cette information afin de prendre des décisions ajustées, mais aussi les adapter en conséquence. Dans une revue de littérature concernant la résolution de problème déductive, Manktelow & Jones, (1987) ont conclu à travers plusieurs études que le contexte ou les paramètres de la situation déterminaient largement l'habilité d'un individu à adopter une stratégie efficace de résolution de problème. Les spécificités d'une situation déterminent l'adoption d'un modèle mental approprié, ce qui mène à la sélection d'une stratégie de résolution de problème adéquate (M. R. Endsley, 1995). Dans l'absence d'un modèle mental approprié, les individus échoueront souvent à résoudre un nouveau problème, même si la logique utilisée est la même appliqué pour résoudre un problème familier (M. R. Endsley, 1995). Le rôle de la CS dans les environnements dynamiques, où plusieurs décisions doivent être prises dans de courts délais, devient alors évident : un opérateur humain qui ne parvient pas à obtenir et maintenir une bonne CS prendra des décisions qui peuvent être inadaptées à la situation, menant ainsi à l'erreur. Il est donc nécessaire que ce dernier soit capable de percevoir correctement les informations pertinentes dans l'atteinte de son objectif.

L'opérateur humain acquière l'information directement de son environnement. Cependant, pour des environnements plus complexes et dynamiques, ces derniers doivent être assistés de systèmes et d'interfaces qui collectent, traitent et leur transmettent les informations importantes. Par exemple, un pilote d'avion sera assisté d'un tableau de bord lui fournissant d'importantes informations essentielles au contrôle de l'avion comme l'altitude, la vitesse, la direction et la consommation de carburant. Pour cette raison, le design des systèmes et interfaces joue un rôle crucial dans l'obtention et le maintien d'une bonne CS en réduisant les efforts cognitifs des opérateurs dans la perception des informations de l'environnement sur les trois niveaux de la CS (particulièrement le niveau 3).

2. Distraction au volant

La distraction au volant se définit comme étant le détournement de l'attention envers les activités essentielles à une conduite sécuritaire vers des activités concurrentes [traduction libre] (Lee et al., 2008). De ce fait, lors de la conduite, un conducteur alloue ses ressources attentionnelles entre la conduite (tâche primaire) et les tâches non liées à la conduite (tâche secondaire). Avec l'acquisition d'expérience, certains aspects de la conduite deviennent automatiques, ce qui permet aux conducteurs d'être en mesure de diviser leur attention entre la conduite sécuritaire et une activité concurrente sans conséquences sérieuses sur les performances de conduites (K. Young & Regan, 2007). Ainsi, un conducteur peut réaliser une tâche secondaire, comme interagir avec un SIE ou être engagé dans une discussion sans que cela provoque un accident. Cependant, c'est lorsqu'un conducteur n'est plus en mesure de diviser son attention entre la tâche primaire et secondaire, et que ses performances de conduites ne sont plus à un niveau adéquat, la distraction au volant survient (K. Young & Regan, 2007). Selon les auteurs, les raisons pour lesquelles un conducteur ne serait plus en mesure de diviser son attention sont : 1) la tâche secondaire est trop complexe ou contraignante et le conducteur n'est pas en mesure d'allouer l'attention nécessaire sur la route, 2) la demande de la route augmente subitement ou est trop élevée pour que le conducteur puisse s'engager dans une tâche secondaire.

Chez un conducteur, la distraction peut émerger de trois sources distinctes (Strayer et al., 2011b). La distraction manuelle lorsqu'un conducteur retire ses mains du volant, cognitive lorsque l'information qu'il traite n'est plus dirigée vers la conduite sécuritaire et la distraction visuelle lorsque son regard n'est plus dirigé sur la route. Cette dernière forme de distraction est considérée comme étant plus importante pour plusieurs raisons. Tout d'abord, l'attention visuelle portée sur la route est intrinsèquement liée à la perception des éléments dans l'environnement (niveau 1) (Cvahte Ojsteršek & Topolšek, 2019) et de ce fait, joue un rôle crucial dans l'acquisition et le maintien d'une CS adéquate. La distraction visuelle exerce aussi une influence plus nuisible sur les performances de conduite à comparer la distraction cognitive et est la principale cause de détérioration des performances de conduite lorsque ces deux formes de distractions sont combinées (Liang & Lee, 2010). En résumé, il est possible pour une personne présentant une déficience motrice ou auditive de conduire, tandis qu'une personne malvoyante ne peut pas exercer cette activité en toute sécurité.

Plusieurs études ont fait état de la relation entre l'attention visuelle dirigée hors route et la probabilité qu'un conducteur soit impliqué dans une collision. Dans l'une de ces études, Green (1999) explique que plus un conducteur regarde longtemps en dehors de la route, plus les chances que celui-ci réalise une collision augmentent. Dans un rapport, (Klauer et al., 2006) ont analysé des données collectées auprès de 100 voitures dans un contexte de conduite naturaliste afin d'identifier les impacts de l'inattention sur les collisions. Les auteurs ont déterminé dans leur analyse qu'un regard hors route de plus de 2,0 secondes est corrélé avec une augmentation des risques de collisions. Alors que 2,0 secondes peuvent sembler un temps assez court, pour un environnement aussi dynamique de la conduite, ce temps représente une préoccupation sérieuse en matière de sécurité routière. En effet, beaucoup peut arriver dans ce court laps de temps. Par exemple, pour une voiture se déplaçant à 100km/h, cette dernière a le temps de parcourir 55,6 mètres en 2,0 secondes. Cela signifie qu'après ce temps, lorsque l'attention visuelle d'un conducteur revient sur la route l'environnement autour de lui n'est plus le même et celui-ci doit à nouveau précéder à une évaluation de la situation afin de réacquérir une CS. De ce fait, ce conducteur ne sera pas en mesure de réagir à un danger imminent. De plus, certaines études suggèrent plutôt un temps en bas de 2,0 s. (Dingus et al., 2006; Horrey & Wickens, 2007; Liang et al., 2014). Lors d'une étude en simulateur de conduite, (Horrey & Wickens, 2007) ont trouvé que lorsque le regard dépasse hors route dépasse 1,6 s., le temps de réaction moyen des participants était de 2,0 s. et que 22% des plus longs regards hors route sont responsable de 86% des collisions observés. Ainsi, plus un conducteur regarde en dehors de la route longtemps, plus son temps de réponse augmente, mais aussi les chances de collisions. Ces résultats sont cohérents avec les résultats de (Liang et al., 2014) qui ont déterminé des résultats similaires lorsque le regard hors route dépassait 1,7 s. Cependant, il est important de faire preuve de précaution lors de l'utilisation de tels seuils puisqu'une collision peut arriver dans un laps de temps plus court que ceux-ci.

3. Les modalités sensorielles pour communiquer

3.1 Les modalités sensorielles

Parce qu'avoir une bonne CS est important pour les opérateurs humains afin d'éviter les erreurs, il est important que les systèmes soient capables de communiquer de manière rapide et efficace les changements afin qu'un opérateur puisse en prendre connaissance le plus rapidement possible. Pour cette raison, le ou les types de modalités utilisées pour transmettre une alerte sont un élément important à considérer afin que celle-ci soit bien perçue par l'opérateur du système.

Les voitures utilisent les modalités auditives (sons et earcons[1]) et visuelles (lumière et icônes) afin de transmettre des informations aux conducteurs. Par exemple, le son qu'émet la voiture lorsque l'on sort de celle-ci en oubliant nos clés ou bien le témoin lumineux signalant un niveau d'essence bas. Cependant, les études sur la distraction au volant démontrent que les alertes visuelles réduisent le temps de réponse des conducteurs à cause de la charge élevée lié à cette modalité dans un contexte de conduite ou l'attention visuelle est un élément primordial (Politis et al., 2014). En outre, les conducteurs dont la charge perceptuelle est élevée, ont significativement moins conscience des stimuli auditifs et visuels que lorsque leur charge perceptuelle est basse. Ce phénomène semble affecter la perception des stimuli visuels plus négativement que les stimuli auditifs pour une même charge perceptuelle (Murphy & Greene, 2015).

Ces résultats mettent en évidence les risques pour la sécurité routière que peuvent causer les interactions avec un système d'infodivertissement embarqué : les conducteurs peuvent manquer le stimulus auditif ou visuel d'une alerte si la demande perceptuelle liée à l'utilisation d'un SIE devient élevée (Cartwright-Finch & Lavie, 2007), entrainant ainsi une cécité d'inattention. Un exemple commun est lorsqu'un conducteur détourne son attention de la route pour interagir avec une interface numérique, comme chercher une chanson dans une liste de lecture ou lire un message. Lors de cette interaction non essentielle à la conduite, le conducteur va diriger son attention visuelle et cognitive vers l'interface, augmentant ainsi sa charge perceptuelle, qui handicape sa faculté à discerner les stimuli l'avertissant d'une collision frontale imminente avec un autre véhicule.

Afin de pallier à ce problème, les chercheurs ont commencé à étudier de nouvelles modalités afin de transmettre des alertes via de nouveaux canaux sensoriels, offrant ainsi une manière prometteuse d'alerter les conducteurs sans causer plus de distraction ou risquer d'être manqué (Dmitrenko et al., 2018; Ho et al., 2005a; Spence & Driver, 1997).

À cause de son emploi prometteur dans la navigation sous-marine et aérienne, la modalité tactile à démontrer être une modalité efficace pour améliorer la conscience situationnelle

[1] Son court et distinctif qui est utilisé pour transmettre une information spécifique ou une notification à un utilisateur. En entendant un earcon, un utilisateur reconnait rapidement l'événement associé à celui-ci. Par exemple, le son d'une notification sur téléphone ou l'alarme d'un micro-onde.

des pilotes (Chiasson et al., 2003; Rupert, 2000). Dans un contexte de conduite automobile, de précédentes études ont montré la fiabilité avec laquelle la modalité tactile peut rediriger l'attention visuelle et augmenter la vitesse de réaction des conducteurs lorsque ceux-ci réagissent à une alerte de collision avant et arrière (Ho et al., 2005a, 2006; J. J. Young et al., 2003). Cette modalité offre aussi d'autres avantages comme ne pas être affecté par une demande visuelle concurrente telle qu'avoir le regard attentif sur la route impose, ce qui en fait une modalité qui s'intègre particulièrement bien dans un contexte de conduite automobile (Sklar & Sarter, 1999). De plus, une étude comparant cette modalité à la modalité auditive démontre que les conducteurs performent aussi bien avec une alerte tactile qu'avec une alerte visuelle (Lee et al., 2004a), alors que les résultats d'autres études suggèrent que cette modalité performe mieux lorsque comparer aux alertes auditives et visuelles (Baldwin & Lewis, 2014; Murata et al., 2017; Scott & Gray, 2008). À ce jour, cette modalité n'est pas encore présente dans aucune voiture sur le marché, mais les études sur celle-ci sont sans équivoque; les alertes tactiles offrent une performance avantageuse pour communiquer auprès des conducteurs dans les automobiles.

Bien qu'utilisée depuis plusieurs années déjà dans le domaine du transport à des fins de marketing et expérientielles (Spence, 2021), la modalité olfactive comme moyen de transmettre des informations à un conducteur a récemment capté l'attention de quelques chercheurs. Dans une étude, (Dmitrenko et al., 2018) ont exploré l'utilisation de l'odeur pour communiquer des messages pertinents à la conduite telle que ralentir, sortie de voie et proximité avec le véhicule devant. Leurs résultats démontrent que les alertes olfactives sont perçues moins distrayantes et plus confortables que les alertes visuelles et que les conducteurs qui expérimentent la combinaison olfactive-visuel font moins d'erreurs de conduites. Les auteurs justifient ces résultats par le fait que les alertes visuelles n'étaient pas assez importantes à comparer les alertes olfactives. De plus, l'utilisation de fragrances associées à une valence positive et un bas niveau d'activation, comme la rose, la menthe ou la lavande, réduisent la colère chez les conducteurs, menant ainsi à un meilleur comportement lors de la conduite (Dmitrenko et al., 2020a; Mustafa et al., 2016) alors que des fragrances associées à un niveau d'alerte plus élevé comme le pamplemousse améliorer les performances de conduites chez les conducteurs somnolents (Fruhata et al., 2013). Bien que la modalité olfactive présente des effets intéressants au niveau des performances de conduites, les études actuelles s'intéressent surtout aux propriétés des fragrances. De ce fait, il n'existe actuellement pas d'étude qui examine le temps de réaction face à une alerte olfactive ni sur les propriétés de cette contre-mesure à rediriger l'attention visuelle d'un conducteur. Les bénéfices liés à l'utilisation de cette modalité ne sont pas les mêmes que ceux liés à la modalité tactile et pour cette raison la contre-mesure présentée dans ce mémoire n'utilisera pas d'alertes olfactives.

3.2 Les modalités combinées

Même si les modalités peuvent être utilisées de manière individuelle pour transmettre des alertes (unimodale), celle-ci sont plus souvent utilisées de manière conjointe (multimodale). Un exemple courant est le son produit par la voiture en combinaison avec un témoin lumineux s'illuminant sur le tableau de bord lorsque le conducteur ne porte pas sa ceinture de sécurité ou lorsqu'une porte est mal fermée. Dans un cas comme ceux-ci, l'avantage d'une alerte multimodale est l'information supplémentaire qui peut être communiquée. Le son attire l'attention du conducteur vers une icône sur le tableau de bord lui montrant une voiture avec les portes ouvertes ou bien celle de la ceinture de sécurité, rendant ainsi l'identification de l'alerte plus aisée.

Dans le contexte de la conduite automobile, le temps de réaction est un élément critique. Un temps de réaction réduit contribue à réduire la distance d'arrêt d'un véhicule en diminuant la distance de réaction du conducteur (distance d'arrêt = distance de réaction + distance de freinage). Par exemple, pour un véhicule roulant à une vitesse de 50km/h il faut environ 37,5m depuis le moment où le conducteur perçoit un danger jusqu'à l'arrêt complet du véhicule (Florida Highway Safety and Motor Vehicle, 2014). Chaque seconde d'inattention supplémentaire augmente cette distance de 13,9m. De plus, un temps de réaction réduit améliore les chances de survie des piétons en cas de collision. Une méta-analyse sur les risques de mortalité pour les piétons révèle qu'à une vitesse de 50km/h, le risque de fatalité pour les piétons est de 29% tandis qu'il est de seulement 5% à une vitesse de 30km/h (Hussain et al., 2019). Ainsi, plus rapidement le conducteur actionne les freins, plus la vitesse du véhicule diminue et plus les chances de survie en cas de collision avec sont élevées. Pour ces raisons, les alertes multimodales qui offrent comme avantages d'être perçue plus rapidement (Diederich & Colonius, 2004), plus facilement (Hancock et al., 2013), et plus urgent (van Erp et al., 2015) sont favorisées par rapport aux alertes unimodales lorsqu'il s'agit de rediriger l'attention visuelle du conducteur sur la route.

Dans une expérimentation, (Diederich & Colonius, 2004) ont testé les combinaisons uni-, bi- et trimodale des modalités auditives, tactiles et visuelles et a pu observer une réduction du temps de réaction entre les stimulus bimodales et unimodales (une combinaison bimodale a un temps de réaction plus rapide que n'importe qu'elle de ses composantes unimodale), mais aussi entre les stimulus bimodales et trimodales (la combinaison trimodale a un temps de réaction plus rapide que n'importe quelle de ses composantes bimodales et unimodales). D'autres études ont tenté de répliquer cette dernière et son arrivée à des résultats similaire (D. Hecht et al., 2005, 2008a, 2008b). Cependant, cet effet est moins prononcé qu'entre les combinaisons bimodales et unimodales. Une étude menée par van Erp et al. (2015) arrive à des conclusions semblables, mais concernant la perception de l'urgence : les combinaisons bimodales et trimodale sont perçues comme étant plus urgente que chacun de leurs constituant unimodale.

À des fins de validité interne, ces études ont mesuré en laboratoire le temps de réaction de participants à l'aide d'un paradigme de signal redondant. Cependant, le contexte dans lequel ces études se sont produites est très différent du contexte de la conduite automobile : la conduite est une expérience de nature multimodale qui se déroule dans un environnement dynamique. Néanmoins, les résultats d'expérimentation en simulateur de conduite démontrent des conclusions similaires en termes d'amélioration du temps de réaction et de l'urgence perçue lorsque les modalités sont présentées de manière bimodale plutôt qu'unimodale (Ho et al., 2007; Politis et al., 2015). Des résultats semblables sont aussi observés pour la conduite dans un trafic de haute et basse intensité (Biondi et al., 2017). Cependant, pour ce qui est du phénomène d'amélioration entre les combinaisons bimodales, et trimodal, les résultats sont mitigés. Dans une étude sur les effets des combinaisons uni-, bi-, et trimodale sur le temps de réponse pour une alerte de reprise de contrôle dans une voiture autonome, (Huang et al., 2019) ont trouvé que le temps de réponse moyen pour une alerte trimodale était plus court, suivit par les alertes bimodales, puis par les alertes unimodales. Des résultats similaires à Huang & Pitts (2020) qui ont déterminé qu'une alerte trimodale est plus facile à détecter chez les adultes, jeunes et âgées, suivit des alertes bimodales. Au contraire, une étude sur les effets d'alertes directionnelles uni-, bi- et trimodale n'ont pas trouvé d'effet d'amélioration entre les combinaisons trimodale et bimodales (Lundqvist & Eriksson, 2019). Résultats aussi similaires à (Politis et al., 2014) qui n'ont pas trouvé d'effet d'amélioration entre les combinaisons trimodale et bimodales (auditive-tactile) pour le temps de réaction à un véhicule avant freinant.

Bien que l'effet d'amélioration entre les combinaisons unimodales et bimodales observé dans les études expérimentales se traduit dans les études en simulateur de conduite, une ambiguïté semble exister concernant ce même effet pour les combinaisons bimodales et trimodale. Le model de ressource multiple de Wickens (2008) offre une justification pour expliquer cette ambiguïté. Selon ce modèle, les individus ont une limite de ressources disponibles pour le traitement de l'information sensorielle, et cette limite est indépendante entre les différents canaux sensoriels (Wickens, 2008). Étant donné que la conduite est une activité qui requiert une forte demande visuelle, le traitement de la modalité visuelle en est handicapé. Par conséquent, il est probable que l'effet d'amélioration entre les combinaisons bimodales et trimodale varie en fonction de la demande visuelle de la tâche routière. Une autre explication possible est que cette ambiguïté soit simplement liée aux aspects expérimentaux utilisés dans les études, tels que le simulateur utilisé, les tâches à réaliser ou les paramètres des alertes.

4. Pistes de solution actuelles

La majorité des automobiles sont équipées de contre-mesures technologiques afin de contrer les conséquences de la distraction au volant. Ces systèmes, comme les systèmes de surveillance de l'état du conducteur (SSEC) et les systèmes d'aide à la conduite (SAC) sont conçus afin d'aider les conducteurs dans la prise de décision, augmentant ainsi l'efficacité de la conduite et la sécurité routière.

4.1 SSEC : Système de surveillance de l'état du conducteur

Les SSEC sont des systèmes utilisés afin de surveiller l'état cognitif d'un conducteur et de les informer lorsqu'il démontre des signes de fatigue, de distraction et de stress afin de l'aider à rester concentré, réduisant ainsi les risques qui y sont liés (Hayley et al., 2021). Dans une revue de la littérature sur les différentes approches pour surveiller l'état du conducteur, (Guettas et al., 2019) font état de trois catégories distinctes. Tout d'abord l'approche physiologique qui collecte des données directement sur le conducteur (ex : EEG, ECG, EDA). Bien qu'utilisée en laboratoire, cette approche reste intrusive, coûteuse et complexe à implémenter dans un véhicule. Ensuite, l'approche comportementale mesure des données en lien avec le comportement du conducteur, mais aussi physiologique à l'intérieur de la voiture (ex : bâillement, clignotement des yeux, le regard, la dilatation de la pupille et la position de la tête). Cette approche beaucoup moins intrusive, mais aussi préférée dans l'industrie automobile (Mandal et al., 2017). Finalement, l'approche basée sur le véhicule qui utilise les senseurs de la voiture afin de d'évaluer l'état du conducteur à travers le comportement de conduite à l'aide de métrique comme le mouvement du volant ou la déviation latérale et longitudinale. Cette approche est aussi peu intrusive et imperceptible pour le conducteur en plus d'être très précise. Cependant plusieurs facteurs externes peuvent influencer les données récoltées par cette approche comme le type de route emprunté, la condition de la route et même la météo. De plus, surveiller le comportement au volant est un indicateur lent de l'état du conducteur (Guettas et al., 2019). En d'autres termes, l'état du conducteur prend un certain temps à se manifester à travers le comportement de conduite.

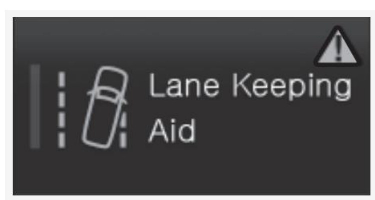
Actuellement, la plupart des nouveaux véhicules produits par les fabricants automobiles tels que Mercedes-Benz, Ford, Volkswagen et Volvo intègrent des SSEC (Ford, 2023; Mercedes-Benz, 2023; Volkswagen, 2023; Volvo, 2020). Pour la majorité de ces manufacturiers, la fonction principale de leur système est de surveiller les conducteurs en cas de somnolence et de les notifier à l'aide d'une alerte sur le tableau de bord. Toutefois, certain fabricant, tels Volvo, vont plus loin et détecte également l'inattention du conducteur et offre des endroits pour se reposer à proximité lorsque la fatigue et la somnolence est détecté (Volvo, 2020). À l'heure actuelle, ces systèmes utilisent tous une approche basée sur le véhicule, mais suite à la démocratisation de technologies derrière les SSEC, comme l'oculométrie et les avancées dans l'intelligence artificielle, l'approche comportementale devient plus accessible, précise et facile à implémenter pour les manufacturiers automobiles. Des compagnies comme Smart Eye et Cipia proposent des systèmes embarqués dotés de caméra et d'oculométrie permettant d'enregistrer des métriques comportementales durant la conduite, améliorant ainsi l'efficacité et la précision des SSEC, mais sans les problèmes liés à l'approche basée sur le véhicule (Cipia, 2022; Smart Eye, 2023).

4.2 SAC : Système d'aide à la conduite

Le deuxième type de contre-mesure est les SAC. Le rôle de ces systèmes est d'aider le conducteur à opérer le véhicule de manière sécuritaire. De manière semblable à l'approche basée sur les véhicules des SSEC, les SAC utilisent les senseurs de la voiture, mais contrairement aux SSEC qui utilisent les données pour inférer l'état cognitif du conducteur, les SAC utilisent les données pour surveiller l'environnement du véhicule et fournir différents types d'assistance selon la situation telle que : prévention de collision, avertisseur de sorties de voie ou les avertisseurs d'angle mort (Marchau et al., 2005). De ce fait, ces systèmes assistent la conduite en avertissant le conducteur d'un possible accident lorsque celui-ci est trop distrait pour s'en rendre compte. Toutefois, il a été suggéré que les SAC, bien qu'ils soient destinés à prévenir les accidents et autres événements imprévues, peuvent avoir des conséquences inattendues (Amditis et al., 2005; Kiefer et al., 2005). Selon une étude menée par (Bliss & Acton, 2003) où ils ont testé différents niveaux de fiabilité pour un avertisseur de collision frontale. Les résultats de cette étude démontrent que le groupe avec 50% de fiabilité avait significativement moins d'accidents avec d'autres véhicules que les groupes avec 75% et 100% de fiabilité. Ces résultats sont compatibles avec une étude réalisée par (Lee et al., 2002), les conducteurs ne tiennent pas en compte et ignorent les avertissements d'un SAC, même s'il indique systématiquement l'imminence d'une collision. Les auteurs ne donnent pas de justification claire de pourquoi les conducteurs ignorent ces alertes, mais ont soulevé deux explications possibles : (1) le manque de compréhension de la nature et de la raison de l'alerte; (2) le manque de confiance envers le système.

Sur le marché automobile actuel, les fonctionnalités des SAC sont assez similaires à travers les fabricants automobiles. Les exemples les plus communs étant : Surveillance et avertissement des angles morts, avertissement de collision avant, avertissement de sortie de voie et assistance au stationnement. Bien que ces systèmes soient présents sur les modèles plus récents, de voiture, ceux-ci font maintenant partie de la majorité de ceux-ci. Selon le Parliamentary Advisory Council for Transport Safety (PACTS) un des problèmes actuels auquel font face les SAC est un manque de standardisation (Helman & Carsten, 2019). Ce manque de standardisation apporte comme problématique que les symboles utilisés pour indiquer le statut d'un SAC ne sont pas toujours claires dans leur signification (Helman & Carsten, 2019). Par exemple, dans une Volvo XC90, le symbole présenté à la **Figure 2** ne sert pas à avertir le conducteur que le véhicule est en train de sortir de sa voie, mais plutôt que le système de maintien de voie est défectueux. De plus, les symboles peuvent varier d'un manufacturier à l'autre, demandant un effort de compréhension supplémentaire à un conducteur. Néanmoins, il a été estimé en 2021 qu'environ le tiers des nouvelles voitures qui ont été vendues aux États-Unis, Japon, en Chine et en Europe possédaient des SAC et que d'ici 2030, plus de la moitié des véhicules sur la route seront équipés de SAC (Cohen, 2022).

Figure 2: *Symbole du système de voie est défectueux d'une Volvo XC90*



Note. Tiré de « XC90 Owner's Manual », par Volvo, 2019, p.130.

4.3 SSEC et SAC : Les lacunes de ces systèmes

Malgré leurs lacunes actuelles, les SSEC et les SAC sont des systèmes bénéfiques qui améliorent la sécurité sur les routes (Hayley et al., 2021; Marchau et al., 2005). Cependant, ces systèmes ne prennent aucune mesure à prévenir la distraction au volant. Les SSEC alertent le conducteur lorsque son état n'est pas propice à une conduite sécuritaire, mais en plus de pouvoir être ignoré, ces alertes ne prennent aucune mesure pour prévenir ou limiter ce changement d'état. De plus, comme énoncé plus haut, ces systèmes surveillent la somnolence et la fatigue au volant et de ce fait, n'interviennent pas en situation ou un conducteur réalise une tâche sans rapport à la conduite. Finalement, leur mode de fonctionnement n'est pas valable pour un état de distraction au volant. Avertir le conducteur à l'aide d'une alerte sur le tableau de bord crée une distraction supplémentaire à laquelle le conducteur doit prendre connaissance avant de retourner son attention sur la conduite. Pour ce qui est des SAC, ces systèmes réagissent aux erreurs et mauvaises décisions des conducteurs en plus de compter sur la réaction d'un conducteur distrait. Par conséquent, les SAC constituent davantage une solution de dernier recours plutôt qu'un moyen proactif d'éviter de tels incidents. Avec les futurs progrès des technologies derrière les SSEC et les SAC, ces systèmes seront en mesure d'être plus précis et efficace dans leur rôle d'appuyer la conduite. Malgré tout, les problèmes liés à la distraction au volant resteront toujours un enjeu en matière de sécurité routière.

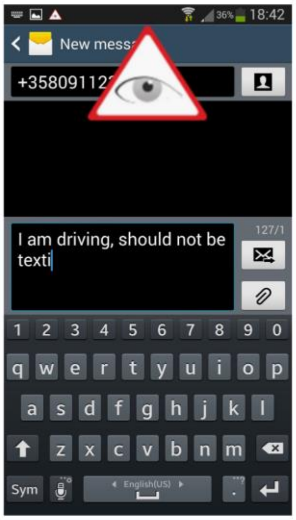
5. Contre-mesure : définition et exemples

Dans ce mémoire, le terme de *contre-mesure* est utilisé pour désigner une mesure proactive visant à prévenir et réduire les risques de sécurité liés au comportement des utilisateurs. Dans le domaine de la sécurité routière, les contre-mesures peuvent être classées en différentes catégories. Tout d'abord, les contre-mesures légales et d'application. Les contre-mesures légales consistent en l'adoption de nouvelles lois visant à améliorer la sécurité routière (Canadian Council of Motor Transport Administration, 2013), telles que le code de la sécurité routière qui limite la vitesse des véhicules et interdit l'utilisation de téléphone en conduisant. Les contre-mesures d'application se concentrent quant à elles sur la mise en pratique de ces lois afin d'augmenter le risque perçu d'être arrêté (Venkatraman et al., 2020), notamment à travers les contrôles routiers et les radars de vitesse. Par la suite, les contre-mesures éducatives prennent la forme de sensibilisation et d'éducation destinées aux conducteurs afin de les informer des risques associés à différents comportements (Venkatraman et al., 2020), comme les campagnes de sensibilisation et éducation envers la population. Ensuite, les contre-mesures d'ingénierie sont des mesures qui influencent les comportements des conducteurs par le biais d'infrastructure routière (AECOM, 2009), telles que les dos d'âne, la signalisation ou les feux de circulation. Finalement les contre-mesures technologiques agissent directement auprès des conducteurs à travers les SSEC et les SAC présents dans le véhicule.

La plupart du temps, plusieurs types de contre-mesures sont mis en place pour faire face à des enjeux de sécurité routière importants comme c'est le cas pour la conduite avec faculté affaiblie (Venkatraman et al., 2020). Cependant, à la connaissance de l'auteur, peu de contre-mesures ont été développées dans l'optique de réduire la distraction causée par l'interaction avec les SIE durant la conduite, malgré des recherches démontrant la nécessité de contre-mesures vis-à-vis le manque d'attention visuel, principalement pour les regards hors route (Victor, 2011). C'est pour cette raison que les efforts de ce mémoire se consacrent à combler ce manque.

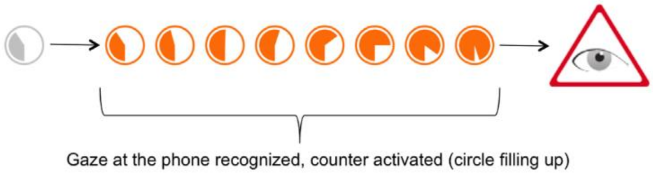
Dans une étude publiée dans le *Journal of Human-Computer Studies*, Kujala et al., (2016) évaluent le prototype d'une contre-mesure technologique servant à atténuer les effets négatifs des conducteurs distraient causé par les appareils mobiles. Ce concept, VisGuard (Kujala et al., 2016), consiste en une application pour mobile qui utilise le téléphone intelligent du conducteur afin de surveiller et d'alerter ce dernier. Pour ce faire, le système enregistre en temps réel le regard du conducteur à l'aide de la caméra frontale du téléphone ainsi que les données GPS pour estimer la demande visuelle en fonction de la position du véhicule sur la route. Lorsque le regard du conducteur est dirigé vers l'écran pour plus de 2,00 s., une alerte visuelle apparait (voir **Figure 3**) pour lui signaler de rediriger son attention sur la route. Un symbole orange est présenté avant l'alerte afin de rappeler au chauffeur de regarder la route avant que le cercle orange soit rempli (voir **Figure 4**). Dans les situations où le GPS détecte une demande visuelle élevée, comme à une intersection ou dans un virage prononcé, le seuil fixe est réduit à 0,00 s. et l'alerte s'affiche automatiquement. Les résultats de cette étude démontrent que la contre-mesure proposée, VisGuard, est efficace à rediriger l'attention visuelle d'un conducteur sur la route. En effet, les participants passaient 5,1% plus de temps visuellement sur la route lors de la tâche de navigation et 29,7% lorsqu'ils devaient rechercher des éléments précis dans un texte (Kujala et al., 2016).

Figure 3: *L'icône d'avertissement du système VisGuard sur l'écran du téléphone intelligent*



Note. Tiré de «Context-sensitive distraction warnings – Effects on drivers' visual behavior and acceptance. », par T. Kujala, 2016, Journal of Human-Computer Studies (90), fig. [1].

Figure 4: *Icônes de l'interface utilisateur : le symbole orange et l'icône d'avertissement et leur taille relative*



Note. Tiré de «Context-sensitive distraction warnings – Effects on drivers' visual behavior and acceptance. », par T. Kujala, 2016, Journal of Human-Computer Studies (90), fig. [3].

Cependant, malgré ces résultats, VisGuard possède certaines limitations. Tout d'abord, il n'y a aucun contrôle sur l'artefact TI puisque la contre-mesure se trouve sur le téléphone intelligent du conducteur. C'est-à dire que le concept VisGuard est limité à l'utilisation que le conducteur en fait avec son téléphone. Ainsi, si ce dernier n'utilise pas ou range sont téléphone durant la conduite la contre-mesure est inutile. Aussi, si un autre conducteur utilise le véhicule et ne possède pas la contre-mesure sur son téléphone, celle-ci est également inefficace. De ce fait, il n'y a aucun contrôle sur si les conducteurs utilisent correctement ou même s'ils utilisent la contre-mesure. Ensuite, VisGuard se concentre spécifiquement sur l'attention visuelle du conducteur envers l'écran du téléphone, ce qui signifie que la contre-mesure ne rend pas en compte les autres éléments de distraction présents à l'intérieur du véhicule, comme les SIE. Finalement, VisGuard utilise une alerte visuelle affichée sur l'écran du téléphone intelligent, ce qui n'est pas optimal et peut même constituer une distraction supplémentaire pour le conducteur. En plus d'utiliser la modalité visuelle qui n'est pas la plus efficace en conduite (Murata et al., 2013; Politis et al., 2014, 2015), la contre-mesure ajoute un élément visuel supplémentaire sur l'interface déjà chargé des téléphones intelligents alors que plusieurs guides recommandent de limiter le nombre d'éléments disponibles sur une interface lors de la conduite (e.g., Commissin of European Communities (2008), the Alliance of Automobile Manufacturers (2003) and Visual-Manual NHTSA Driver Distraction Guidelines for In-Vehicle Electronic Devices (2013)). La contre-mesure proposée dans ce mémoire prend en compte les lacunes du concept VisGuard et en propose une version plus adaptée au contexte actuel de la conduite. La description de la contre-mesure proposée dans ce mémoire se retrouve dans le chapitre 2, dans la section méthodologie de l'article.

L'objectif de cette revue de littérature était de synthétiser les recherches actuelles liées aux thèmes abordés dans ce mémoire. Tout d'abord, l'importance de l'attention visuelle sur la route est soulignée en raison de son lien avec l'acquisition et le maintien d'une conscience de situation appropriée, ce qui est essentiel pour une conduite sécuritaire (Cvahte Ojsteršek & Topolšek, 2019). Bien que de nombreuses études aient examiné la relation entre l'attention visuelle détournée de la route et la probabilité d'une collision, la durée pendant laquelle le conducteur détourne le regard de la route reste encore à explorer. Des études ont suggéré des durées telles que 2,0 s. (Klauer et al., 2006), 1,7 s. (Liang et al., 2014) et 1,6 s. (Horrey & Wickens, 2007). Cependant, il est important de prendre des précautions lors de l'utilisation de tels seuils, car une collision peut se produire en un laps de temps plus court. Peu d'expérimentations ont mis en pratique ces seuils afin d'évaluer leur impact sur la conduite et les lors d'interactions avec différents artéfacts TI. Ensuite, cette revue de littérature examine également les études empiriques sur les modalités sensorielles des alertes automobiles. Dans cette section, la présence d'un effet d'amplification est mentionnée lorsque les modalités auditive, tactile et visuelle sont combinées en binôme (Biondi et al., 2017; Ho et al., 2007; Politis et al., 2015) et en trinôme (Diederich & Colonius, 2004; D. Hecht et al., 2005, 2008a, 2008b). Cependant, l'existence de cet effet d'amplification dans un contexte de conduite pour la combinaison trimodale reste ambiguë. Certaines études ont montré sa présence (Huang et al., 2019; Huang & Pitts, 2020), tandis que d'autres non (Lundqvist & Eriksson, 2019; Politis et al., 2014). Des investigations supplémentaires sont nécessaires pour parvenir à des conclusions et pour clarifier les raisons de ces résultats contradictoires.

Ce mémoire présente une contre-mesure qui utilise les données physiologiques d'un conducteur afin de rediriger son attention sur la route lorsque celui-ci est visuellement distrait. Les résultats de l'évaluation de cette contre-mesure dans le prochain chapitre répondent aux manques de connaissances soulevé précédemment. Bien que ceux-ci n'apportent pas de réponse définitive, ils représentent un premier effort.

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Chapitre 2: Article scientifique

A gaze-based driver distraction countermeasure: Comparing effects of multimodal alerts on driver's visual attention

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Abstract

In this study, we introduce and evaluate a novel countermeasure that uses real-time eye-tracking data to detect instances where the driver's gaze deviates from the road beyond a predetermined threshold, then redirects the driver's attention back on-road through bimodal and trimodal alerts from the combination of the auditory, tactile and visual modalities. This new countermeasure advocates for the adoption of eye-tracking technologies to help monitor and mitigate driving distractions while also proposing an additional layer of safety for driving distraction mitigations systems such as driver monitoring systems (DMS) and advanced drivers' assistance systems (ADAS). In our study, participants conducted different levels of interaction with an in-vehicle infotainment system (IVIS) within a driving simulator with and without the countermeasure. Additionally, each participant was randomly assigned to one of four alert combinations: 1) auditory-tactile, 2) auditory-visual, 3) tactile-visual and 4) auditory-tactile-visual. Our results indicated that the countermeasure effectively redirected drivers' visual attention to the road; the proportion of time participants spent with their gaze on-road was higher when the countermeasure was present compared to its absence. Furthermore, our findings revealed that bimodal alerts including the visual modality were less effective at redirecting participants' gaze on-road and resulted in poorer driving performance than the auditory-tactile combinations. Moreover, there was no evidence supporting the idea that trimodal alerts would be more effective than the ultimately more effective bimodal combinations (in this case auditory-tactile) in redirecting visual attention to the road and improving driving performance.

Keywords: Countermeasure, in-vehicle infotainment system, driving distraction, sensory modalities, driving simulator, road safety, haptic, warning system, situation awareness.

1. Introduction

Driver distraction is a common cause of traffic accidents and has been the subject of numerous studies in the field of transportation safety. A growing number of automobile accidents are related to drivers being distracted, varying between 5% to more than 25% of all crashes in Europe, depending on the type of the study or the definition used (Hurts et al., 2011). In Canada, it represented 25.3% of all road fatalities in 2017 (Brown et al., 2021), and in the United States, it represented 8.74 persons killed per day because of crashes involving distracted drivers in 2019 (Stewart, 2022). It is difficult to assess the real implication of driver distraction because the phenomenon is underreported. For example, people do not always reveal they were distracted when they were involved in an accident. However, a study using naturalistic driving data showed that distraction was a factor in 68.3% of all the crashes observed (Dingus et al., 2016).

Given the significant consequences associated with driver distraction and its implications for road safety, the study of the effects of in-vehicle infotainment systems (IVIS) on driver distraction is a pertinent subject within the domain of human-computer interaction. IVIS can be described as electronic systems that provide entertainment and information to the driver such as navigation, music, communication and other features that are not essential to the operation of the vehicle (Strayer et al., 2017). The benefit of these systems is to enhance the driving experience and provide convenience to the driver. Some common examples of IVIS include dashboard display, touch-screen interface, and voice-activated controls.

While IVIS can provide valuable real-time information to drivers concerning route guidance, traffic congestion, and preemptive hazard alerts, it’s imperative to recognize that IVIS also have potential risks. IVIS-induced distraction can be an issue, particularly with the diversionary potential inherent in their entertainment functionalities, often encompassing non-essential activities unrelated to the task of safe driving during their interaction (Ramnath et al., 2020). Furthermore, the proliferation of such systems raises concerns for road safety and is exacerbated by the projected growth of the automotive infotainment system market, which is estimated to expand from $10.035 million in 2021 to $20.720 million by 2030 (Research Dive, 2022).

Interacting with an IVIS require drivers to shift their visual focus towards the dashboard display, thereby diverting their visual attention away from the roadway. This shift of attention from driving-related tasks to non-driving tasks has been consistently associated with compromised driving performance. This impairment encompasses slower reaction time to hazardous situation (Strayer et al., 2017), slower driving speed (Platten et al., 2013) and increase in lateral and longitudinal lane deviation (Ramnath et al., 2020). Some have even suggested that many of the features provided by IVIS should not be available when driving due to their excessively distracting nature (Ramnath et al., 2020). Although IVIS are being designed to optimize driver's information processing (Platten et al., 2013), several studies have consistently demonstrated that interacting with an IVIS while driving significantly undermines on-road visual attention and overall driving (Blanco et al., 2006; Reyes & Lee, 2004; Strayer et al., 2017; Strayer et al., 2019).

Existing research shows that the transportation industry is aware of the consequence of IVIS distraction. In response, some guidelines have been created to constrain manufacturers to mitigate the workload imposed on the driver by these interfaces, exemplified by initiatives like those set forth by the Commission of the European Communities (2008) and the Alliance of Automobile Manufacturers (2003). Even with those requirements already in place, it has been acknowledged by the National Highway Traffic Safety Administration (NHTSA) that several IVIS features still engender excessive distractions for drivers. Consequently, the NHTSA has developed its own guidelines for in-vehicle electronic devices aiming to promote safety by discouraging the introduction of excessively distracting devices (National Highway Traffic Safety Administration, 2013). However, research on the effect of IVIS on driving performance finds that the eye gaze behavior when using touch control fails to meet the NHTSA standard (Ramnath et al., 2020), even with Apple CarPlay and Android Auto, two IVIS software which have a significantly lower cognitive demand on drivers than the original equipment manufacturer systems (OEM) (Strayer et al., 2019). Despite the effort behind those recommendations, it is crucial to acknowledge that these guidelines are non-compulsory and consequently, often evade thorough consideration by manufacturers.

Some countermeasures exist for assisting drivers in their primary task of safe driving like advanced driver assistance systems (ADAS). These systems are designed to help drivers in operating their vehicle safely by reacting to driver's mistakes or misjudgments, thereby encompassing functionalities like collision prevention, lane keeping assistance, and blind-spot monitoring (Marchau et al., 2005). Yet, it's crucial to note that ADAS primarily operate reactively to distraction-induced errors rather than proactively preventing them. Alternatively, driver monitoring systems (DMS) have been introduced to assess driver's cognitive state and warn them when drowsiness, distraction and stress are detected, in order to mitigate the risks associated with such states (Hayley et al., 2021). However, DMS merely trigger alerts without taking subsequent actions based on the driver's assessed state. While these countermeasures are proven systems that enhance road safety (Hayley et al., 2021; Masello et al., 2022), they do not present a comprehensive solution for pre-emptively preventing IVIS distractions.

There is some similarity between smartphones and IVIS in terms of interactions (touch screen display and voice control) as well as functional attributes (navigation, auditory content consumption, and communication). However, there are some differences in form of laws and design. Manipulating smartphones while driving is prohibited in numerous countries due to the consequences on road safety (World Health Organization, 2018). Smartphone manufacturers have also designed a driving mode that restricts smartphone functionalities, permitting only voice-based interactions for functions like send messages, make calls and control media (*Get started with Google Assistant driving mode - Google Assistant Help*, 2023; *Use the Driving Focus on Your iPhone to Concentrate on the Road*, 2022). In contrast, within the domain of IVIS, there is currently no publicly marketed or readily accessible countermeasure explicitly tailored to mitigate IVIS-induced distractions.

There is some existing research that studies the integration of eye-tracking technologies into ADAS and DMS. However, to date, no investigation has examined the potential of an eye-tracking-based countermeasure as a preventive measure against IVIS distraction. In the context of addressing visual inattention as a means to advert driver distraction, Kujala et al. (2016) assessed the impact of a smartphone-based context-sensitive countermeasure (in-car glance data) alongside GPS information to capture and estimate the visual demands imposed by specific road locations. However, the efficacy of this countermeasure hinges upon the position and the countermeasure being install on the phone. Its effectiveness its contingent upon the driver's willingness to deploy and use it. Moreover, this countermeasure exclusively addresses the driver's visual engagement with the smartphone display, neglecting the potential for other in-vehicle distractions. Furthermore, the countermeasure exhibits a visual alert via the smartphone interface, a strategy which stands in contrast to many guidelines advocating for limiting the number of elements accessible on an interface while driving (e.g., Commissin of European Communities (2008); the Alliance of Automobile Manufacturers (2003); National Highway Traffic Safety Administration (2013)).

In this paper, we aim to evaluate the efficacity of a new countermeasure design for redirecting drivers' visual attention to the road when their off-road gaze exceeds a predetermined threshold. Thus, our first research question is: **how effective is a countermeasure that take a driver's eye gaze into account in redirecting a driver's visual attention from an IVIS to the road?**

If this countermeasure is efficient, this opens another area of inquiry: how can the eye-gaze-based countermeasure best alert drivers? For notifying drivers ADAS use auditory and visual alert modalities, with some recent research also showing the promise of the tactile modality to enhance efficacity of alerts in a driving context (Baldwin & Lewis, 2014; Ho et al., 2005a, 2006; Sklar & Sarter, 1999; Young et al., 2003). In addition, research has demonstrated that two-way combinations of those modalities (bimodal) enhance reaction time (Diederich & Colonius, 2004; van Erp et al., 2015). However, the impact of this enhancement effect in a driving context is still unclear for trimodal combinations. To examine this in the context of driving with the proposed eye-gaze-based countermeasure, our second research question is: **which combination of auditory, tactile**

and visual modalities is the most effective in redirecting driver's visual attention from an IVIS to the road?

Two experiments were conducted to examine these questions. In the first experiment, we used a bimodal combination of auditory and tactile alerts for redirecting the driver's visual attention to the road. This combination was chosen over the other bimodal combination (auditory-visual and tactile-visual) because of its better performance at redirecting drivers attention based on previous studies on ADAS. The trimodal combinations was not selected because its efficacy has not yet been clearly demonstrated in a driving simulation context. The second experiment includes all bimodal combinations of auditory, tactile and visual modalities as well as their trimodal combination.

In the next section, a comprehensive literature review will be presented to establish the requisite context and knowledge essential for comprehending and justifying the study, as well as presenting the relevant hypotheses related to this research. The ensuing empirical paper will be divided into two main sections, experiment 1 and 2, each encompassing its corresponding methodology, results, and subsequent discussions. In experiment 1, participants were exposed to the countermeasure while interacting with an IVIS during driving sessions in a driving simulation. Results show the efficacy of the countermeasure in redirecting drivers' visual attention toward the road. In experiment 2, similar conditions were replicated, but participants were divided into four groups, each experiencing a different combination of alerts. Results demonstrate that bimodal alerts, which include the visual modality, are less effective in redirecting participant's gaze towards the road and poorer driving performance than the auditory-tactile combination. Following this, a comprehensive synthesis of the findings from both experiments is presented in the general discussion, establishing connections to the existing body of knowledge in the academic literature. Finally, a conclusive summary will bring closure to this paper.

2. Literature review

2.1 IVIS impacts on driving

On-road visual attention studies have shown that crash probability increases linearly with the time spent visually off-road by drivers (Green, 1999) and that a glance greater than 2 seconds away from the road are correlated with increased crash/near-crash risk (Klauer et al., 2006). While a 2-second time lapse may seem relatively short, it represents a critical concern for road safety due to everything that can happen within this time. For example, a car traveling at 100km/h travels 55.6 meters in 2 seconds. This means that when the driver's attention comes back on-road, the environment around them needs to be re-assessed because the driving environment is a dynamic environment. Some studies suggest that a glance away from the road should not exceed 1.6 seconds (Dingus et al., 2006; Horrey & Wickens, 2007) or 1.7 seconds (Liang et al., 2014) instead of the previous 2-seconds. Such a time threshold should be carefully used because time away from the road is not the only factor leading to accidents. Drivers also need to be aware of the situation around them in order to be able to assess their environment, because accidents tend to occur when the road demand and the IVIS demand exceed the driver's maximum capacity to manage them (Lee et al., 2008). While interacting with an IVIS, drivers tend to react more slowly to hazardous situations (Strayer et al., 2017). For example, a study found that the reaction time of drivers was significantly higher when manually and vocally selecting a song on a IVIS as compared to driving impaired by cannabis, alcohol, or talking handsfree on a phone (Ramnath et al., 2020). The same study also found that manually interacting with an IVIS resulted in a worse reaction time than holding a phone for conversation or texting.

As for smartphone distraction, several studies found that interacting with an IVIS while driving also significantly impairs driving performance. For example, a study found that drivers slow their driving speed while interacting with an IVIS (Platten et al., 2013; Ramnath et al., 2020) which is in line with previous research where participants tended to slow the driving speed when handling a phone (Iio et al., 2021). This can be explained by the fact that drivers that engage in a secondary task reduce their speed to manage the additional workload while driving. Furthermore, despite drivers reducing their speed, both the lateral (lane deviation) and longitudinal (maintaining a safe distance with the vehicle in front) are affected when interacting with an IVIS (Ramnath et al., 2020). Moreover, distracted drivers are more susceptible to miss roadway indications and have poorest driving performance (Donmez et al., 2006; Horberry et al., 2006; Oviedo-Trespalacios et al., 2016).

Therefore, we argue for the first experiment that driving with the countermeasure will result in **increased on-road visual attention,** as well as **improve driving performance** during IVIS interactions, in comparison to driving without the countermeasure.

H1.a: driving with the countermeasure will result in **increased on-road visual attention** during IVIS interactions, in comparison to driving without the countermeasure.

H1.b: driving with the countermeasure will result in **improve driving performance** during IVIS interactions, in comparison to driving without the countermeasure.

Moreover, drivers subject to high workload have visual detection impairment (Recarte & Nunes, 2003) and longer reaction time (Makishita & Matsunaga, 2008; Müller et al., 2021), the countermeasure should not increase driver's workload to be efficacious. Because previous studies have used vibrotactile feedback to reduce driver's workload and see fewer distractions and navigational errors (Borojeni et al., 2017; Ege et al., 2011), we believe for the first experiment that driving with the countermeasure will result in **lesser workload** in comparison to driving without the countermeasure.

H1.c: driving with the countermeasure will result in **lesser workload** in comparison to driving without the countermeasure.

2.2 Current solutions

One type of countermeasure that can be found in recent vehicles is driver monitoring systems (DMS). These systems track the driver's cognitive state and warn them when drowsiness, distraction and stress is detected, in order to reduce the risks associated with those states (Hayley et al., 2021). Guettas et al. (2019) divide those systems into three categories. The first is physiological approach, which consists of collecting data directly from the driver (e.g., electroencephalogram [EEG], electrocardiography [ECG], electrodermal activity [EDA]). This approach is mainly used in laboratory because it is costly, intrusive and complex to implement in vehicle. The second is behavior approach, where data is collected from drivers' behavior and drivers' physiological data (e.g., blinking rate, gaze position, pupil dilatation or head position). This approach is less intrusive than the physiological approach and is preferred by the automobile industry

(Mandal et al., 2017). Thirdly, the vehicle-based approach consists of data collected by the vehicle sensors (e.g., steering wheel movement, lane deviation, acceleration and braking). While also non-intrusive, vehicle-based DMS are also accurate, but sensitive to external factors like the weather, type of roads or road condition (Guettas et al., 2019). Many popular car manufacturers like Ford, Volvo, Mercedes-Benz, etc. have already integrated vehicle-based DMS in their vehicles, under different names. One major drawback of those systems is that they do not take any action after assessing a distracted driver state other than displaying a message through the dashboard that can be discarded (Ford, 2023; Mercedes-Benz, 2023; Volvo, 2020). Thus, DMS alert drivers about the state of their alertness, but do not take any action in order to prevent it. Moreover, vehicle-based DMS are slow indicator of a driver's state, meaning that it takes some time to manifest itself in driving behavior (Guettas et al., 2019). However, due to new advances in the technologies behind DMS, companies like Cipia or Smart Eye develop new systems that allow for easier implementation of more efficacious behavioral approach DMS (Cipia, 2022; Smart Eye, 2023).

Another type of countermeasure found in current vehicles is advanced driver assistance systems (ADAS), whose role is to assist drivers in operating their vehicle safely. These systems infer potential distraction from the driver by a combination of sensors and other technology to monitor the driver's environment and provide them with various types of assistance, such as collision prevention, helping keep the vehicle in lane, or blind spot monitoring (Marchau et al., 2005). The goal of ADAS is to keep the driver safe by assessing and reacting when the consequences of distracted driving are manifesting. However, it has been suggested that ADAS systems, despite being intended to prevent accidents and other unplanned events, may themselves have unintended consequences (Amditis et al., 2005; Kiefer et al., 2005). According to one study, drivers discount or ignore warnings even if it consistently indicates an impending collision (Lee et al., 2002). The authors did not provide a clear reason why drivers are ignoring them, but they have raised two possible explanations: (1) driver's lack of comprehension of the nature and purpose of the warnings; (2) driver's lack of trust in the warning system. Moreover, Bliss and Acton (2003) have tested a forward collision warning system with different levels of reliability. They have found that the group with a 50% reliability had significantly fewer accidents with other vehicles than the groups with 75% and 100% reliability (Bliss & Acton, 2003). Because ADAS react to driver's mistake or misjudgment, they rely on the reaction of a distracted person. Therefore, they are more about providing a last-resort solution rather than being a proactive means of avoiding such incidents. Another concern with ADAS that has been raised by the Parliament Advisory Council for Transport Safety (PACTS) is a lack of standardisation in the symbol used for communicating ADAS' status, which leads to an unclear meaning for the drivers (Helman & Carsten, 2019).

2.3 Modalities to redirect drivers' attention

For communicating and notifying drivers, in-vehicle technologies use different modalities, most commonly auditory and visual alerts in the form of sounds, lights, earcons[2] and icons. Yet, with in-vehicle technologies like IVIS and ADAS, we see a proliferation of alerts creating an excess of different signals that create confusion for drivers and reduce the effects of such alerts. Studies on driving distraction provide evidence that visual warnings slow the response time of drivers because of the high perceptual load this modality brings in a driving context (Politis et al., 2014). In addition, drivers under high perceptual load have a significantly lower awareness for auditory and visual stimuli than under low perceptual load. Moreover, the perceptual load seems to have had a greater negative effect on awareness of visual stimuli than auditory stimuli (Murphy & Greene, 2015). This results in the alert being missed when the visual and auditory demands of the driving task are too high, a phenomenon called inattentional blindness (Cartwright-Finch & Lavie, 2007). Hence, researchers have assessed new modalities for conveying alerts via new sensory channels, offering a promising way to convey information to drivers without causing more distraction or risking being missed.

Because of its very successful employment in aerospace and underwater navigation, tactile seems a promising modality for enhancing driver situation awareness (Chiasson et al., 2003; Rupert, 2000). Previous studies have shown the reliability of this modality to redirect driver visual attention in the context of reacting to a forward and rear-end

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[2] Short and distinctive sound used to convey specific information or notification to a user. By hearing an earcon, a user quickly recognizes the event associated with it. For example, the sound of a phone notification or a microwave ready alarm.

collision warning and that drivers were reacting earlier with this modality than without it (Ho et al., 2005a, 2006; Young et al., 2003). Moreover, when using tactile modality, the detection and reaction time are not affected by concurrent visual demands, thus making this modality a great complement to driving (Sklar & Sarter, 1999). When comparing tactile modality to others, some research has shown that drivers perform similarly with tactile and auditory alerts (Lee et al., 2004a), and some have shown that tactile alerts perform better when compared to auditory and visual alerts (Baldwin & Lewis, 2014; Murata et al., 2017; Scott & Gray, 2008). These findings suggest that tactile modality can enhance the efficacy of alerts in a driving context.

A well-studied phenomenon named the Colavita visual dominance is based on participants often failing to respond to an auditory or tactile alert when in combination with a visual alert although they have no problem adequately responding to those modalities when presented individually (Colavita, 1974; Hartcher-O'Brien et al., 2008), meaning that visual alerts are less likely to go unnoticed. Hecht & Reiner, (2009) investigated in a laboratory experiment if this effect is also present in a trimodal combination. They conclude that the Colavita effect is limited to bimodal combination and raise as explanation that the probability of missing two signals is lower than missing only one. In addition, they find no natural hierarchy between auditory and tactile alerts. However, because driving demands an important level of visual attention, visual alerts have a slower reaction time than auditory and tactile alerts in high urgency situations in a driving simulation context (Murata et al., 2013; Politis et al., 2014, 2015). Thus, bimodal alerts that include a visual modality are impaired. On the contrary, it has been shown that auditory-tactile bimodality can promote faster reaction time to hazards (Murata et al., 2012, 2013). Making it, in a driving context, the more efficacious bimodal combination for redirecting driver attention to the road.

It is expected in the second experiment that bimodal combination incorporating the visual modality will be less effective at **increasing on-road visual attention** as well as **improving driving performance** during IVIS interactions, in comparison to the bimodal combination with only the auditory-tactile modalities. Thus, it is expected that auditory-tactile combination will be the more effective bimodal combination.

H2.a: bimodal combination incorporating the visual modality will be less effective at **increasing on-road visual attention** during IVIS interactions, in comparison to the bimodal combination with only the auditory-tactile modalities.

H2.b: bimodal combination incorporating the visual modality will be less effective at **improving driving performance** during IVIS interactions, in comparison to the bimodal combination with only the auditory-tactile modalities.

Researchers have assessed the combination of the three modalities (auditory, tactile and visual) in non-driving related studies and found that the bimodal combination of those modalities had a positive effect on reaction times, which were faster than those of their unimodal components (Diederich & Colonius, 2004; D. Hecht et al., 2005, 2008a, 2008b). The same studies have also indicated this effect also exists beyond bimodal combinations where the trimodal combination is detected faster than the fastest of its bimodal constituents and that the magnitude of this effect seems to be smaller for the trimodal combination than for bimodal ones. Moreover, it is also suggested that multi-modal alerts are perceived as more urgent than each of their unimodal constituents (van Erp et al., 2015). This implies that the combination of multiple modalities effectively enhances the reaction time, more than any of their modality's constituent. This means that there is great added value for multimodal alerts in a situation where a uni-modal alert would be less salient or where reaction time is a crucial factor, such as redirecting driver attention rapidly toward an imminent danger.

In a driving context, multiple studies have reached similar conclusions: Reaction time is smaller and perceived urgency is higher for alerts for which modalities are presented conjointly (Ho et al., 2007; Politis et al., 2015). In addition, Biondi et al. (2017) found that bimodal alerts produce faster responses than their unimodal counterparts in high-density traffic. They are also as effective in heavy traffic as in less dense situations. In a study on autonomous vehicles, Huang et al. (2019) investigate the effects of uni-, bi- and trimodal combinations on response time for take-over alerts. They found that the average response time for the trimodal combination is the shortest, followed by bimodal, then by unimodal. Similar results have also been found by Huang & Pitts, (2020) who determine that trimodal alerts are the easiest to detect for both young and older adults, followed by the bimodal alerts (with no significant difference between them). However, different results are also found with trimodal alerts in a driving context. For example, (Politis et al., 2014) did not find any advantages of the trimodal combination over the auditory-tactile combination for the response time when reacting to a presentation of a car braking. Moreover, another study on the effect of uni-, bi- and trimodal directional warnings on young and old drivers' responses in a driving simulator finds no enhancing effect on the trimodal combination over the bimodal combinations (Lundqvist & Eriksson, 2019). While the improvement of the modalities effect in bimodal combinations observed in experimental studies translates in driving simulation studies, the same effect does not seem to be entirely translated for the trimodal combination.

Despite this ambiguity, we hypothesize that the trimodal combination will be more effective than all bimodal combinations at **increasing on-road visual attention** as well as **improving the driving performance** during IVIS interactions.

H3.a: trimodal combination will be more effective than all bimodal combinations at **increasing on-road visual attention** during IVIS interactions.

H3.b: trimodal combination will be more effective than all bimodal combinations at **improving the driving performance** during IVIS interactions.

A. Experiment 1

A1Methodology

Experiment 1 is design to test hypothesis 1 (H1.a, H1.b, H1.c), answering the question: how effective is a countermeasure that takes a driver's attentional state into account in redirecting a driver's visual attention from an IVIS to the road?

A1.1 Participants

For the first experiment, participants ranged in age between 21 and 46 (mean = 26.57, SD = 5.51), with 8 identifying as males and 13 as females, for a total sample size of 21 participants. Each participant received a compensation of $30 for their participation. Participants were recruited via a research panel and were screened for inclusion in the study. All participants had to be 18 years old, have a valid driver's license in our jurisdiction (the simulator in this study uses the traffic code of this jurisdiction), wear appropriate footwear, not be susceptible to certain conditions (motion sickness, epilepsy, or skin allergies), or require glasses to drive.

A1.2 Experimental design

For this study, we conducted a two-factor within-subject experiment in which the exposure to the countermeasure as well as the difficulty of the interaction based on the visual demand required to complete them was manipulated (see **Figure 5**), with on-road visual attention, driving performance, and subjective workload as the main dependent variables. The experimental session consisted of driving the same road three times, twice with the countermeasure and once for the control condition (CM1, CM2, Control) (see **Table 2**). In this study, it was decided to have a second condition were participants drove with the countermeasure for a second time (CM2) because we wanted to investigate if participants would be more accustomed to it over time. In addition, the order was counterbalanced with participants randomly receiving one of the three following sequences: (1) CM1→CM2→control (2) CM1→control→CM2 (3) control→CM1→CM2

Figure 5: *Experimental protocol of the first experiment*

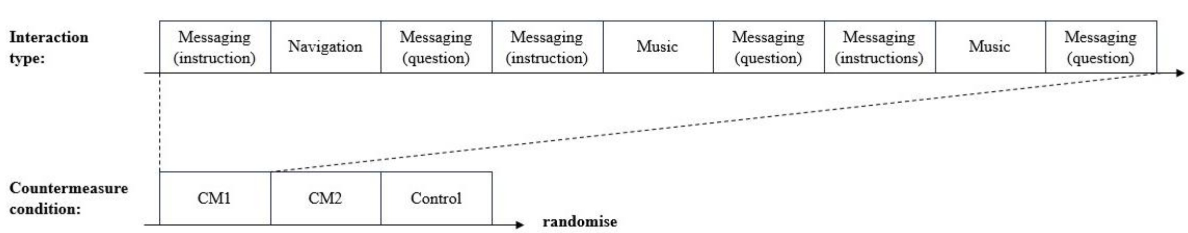


Table 2: *Independent variable: exposition to the countermeasure.*

Countermeasure exposition condition	Definition
CM1	The condition where participants drove with the countermeasure for the first time.
CM2	The condition where participants drove with the countermeasure for the second time.
Control	The condition where participants drove without the countermeasure.

During each driving condition, participants had to interact with an IVIS with three different levels of difficulties based on the visual demands required by the task (see **Table 3**). In the low difficulty interaction, participants had to interact with a messaging application in which they had to listen to and sometimes respond to a message. Certain messages gave driving instructions that the participants had to follow (MESSAGING-INSTRUCTIONS), and asked a question to which participants had to provide a simple answer (MESSAGING-QUESTION). These interaction were deemed low difficulty because the application can be used by vocal commands or simple manual buttons to confirm an action. In the medium difficulty interaction, participants had to interact with the NAVIGATION application where they had to enter a generic destination (e.g., Museum) using a verbal interaction and then select manually from a list of specific locations (e.g., Museum of Fine Arts). This interaction was considered medium difficulty because the participant had to search through a list, but no scrolling was required. Finally, the high difficulty interaction was with a MUSIC application in which participants had to find a playlist, then a specific song on it (e.g., in the playlist Top 80s, play the song “Call me” by Blondie). This interaction was considered high difficulty because participants had to navigate to the right playlist and then manually scroll down to find the song. There were 16 songs in each playlist.

Table 3: *Type of interactions participants had to partake in during each condition and their difficulty level.*

Interaction type	Interaction difficulty	Interaction steps
Messaging-instructions	Low	1. Open the messaging app.
		2. Select the contact
		3. Listen to the instructions
Messaging-question	Low	1. Open the messaging app.
		2. Select the contact
		3. Listen to the question
		4. Respond to the question
		5. Confirm sending the response
Navigation	Medium	1. Open the navigation app.
		2. Research
		3. (E.g.) Pet Store
		4. Browse (7 items, no scrolling)
		5. Start the itinerary
Music	High	1. Open the music app.
		2. Browse playlist (5 items, no scrolling)
		3. Browse songs (16 items, scrolling)

A1.3 Apparatus and instruments

The study was conducted via a driving simulator in a usability laboratory setting. The simulator was composed of a t-slot frame to which a driving seat (OMP Design2), a steering wheel and a pedal set (Thrustmaster T-GT II) were attached. The simulator software was City Car Driving (Forward Development, Novosibirsk, Russia) and was run with a PC and displayed on a 49-inch curved Samsung CHG90 QLED Gaming Monitor (Samsung, Suwon, South Korea). For the sound, two Logitech X-240 speakers (Logitech, Lausanne, Switzerland) were connected to the PC and placed behind the monitor.

To simulate an IVIS, an Android tablet (Google, Mountain View, United States) was attached to the frame with a support designed and 3D printed by the research team (see **Figure 5**). The tablet was positioned so the left edge of the screen was 12 cm from the steering wheel and the bottom edge of the screen was 66.5 cm from the ground. Apple CarPlay (Cupertino, United States) was the application interface used in this study because it is an accessible and commonly used IVIS application, as well as for its ease of implementation. To implement it, a Carlink CPC200-Autokit dongle (Carlinkit, China) was used to emulate CarPlay by connecting an iPhone XR (Apple, Cupertino, United States) to the Android tablet. In this experiment, the applications used were Apple Plans and Apple Messages, which are natively on the iPhone, and Spotify, (Spotify AB, Stockholm, Sweden) which was installed. There were no other applications on the iPhone except those that come by default with the iPhone.

To track participants' visual attention throughout the experiment, the Smart Eye Pro (Smart Eye AB, Gothenburg, Sweden) eye tracker was used. The eye tracker is composed of two cameras that capture the data which were placed in front of the monitor, at the left and right bottom corner, so they could account for most of the height disparities between participants.

Figure 5 : Driving simulator setup

A1.4 Countermeasure design

To answers the first research question, a countermeasure was designed and developed. The purpose of this countermeasure is to help drivers maintain an appropriate visual attention on-road during driving by alerting the driver when their off-road gaze exceeds a threshold of 1.6 seconds so that driver can redirect their visual attention on-road. The established threshold is based on the finding of Dingus et al. (2006) and Horrey et Wickens (2007). The alert in experiment 1 is a bimodal combination of auditive and tactile modalities presented through sound and a haptic seat.

A.1.4.1 Tactile and auditive alerts

A vibrotactile seat cushion was specifically designed by our team to send the tactile modality alerts to the driver. The cushion consisted of 10 mini vibrating motors (Adafruit – Vibrating mini disk motor) that were inserted in foam so that the participants would be more comfortable sitting on them. Six vibrating motors were positioned in the bottom cushion where the driver sits, and four were positioned in the back cushion (see **Figure *6* :** Picture of the vibrotactile seat and the plan of the disposition of the mini vibrating motors on the seat cushionThe vibration frequency used in this study was effect #118 from the Arduino library (Adafruit_DRV2605 Library). Moreover, to protect and stabilize the tactile cushion while people are sitting on it, a textile cover was made. The cover was black to match the color of the driver's seat so that participants would not notice it. Participants were informed about the presence of the cushion but were only informed about the tactile alert before a task involving one. None of the participants made remarks about the presence of the cushion on the car seat during the study. To protect the mini vibrating motors and stabilize the cable connection of the motors to the electrical circuit from wear, a shell was also designed (see **Figure 7**).

For emitting the auditive alerts, a simple speaker (Adafruit Speaker 3" Diameter 4 Ohm 3 Watt) was used. The speaker was placed on the table in front of the curved monitor. The sound for this alert was the conventional red alarm used by Philips Intellivue Patient Monitoring for life threatening situations (Philips, Amsterdam, The Netherlands). It is a common high-priority alarm used in the medical field. Finally, the vibrotactile seat cushion and the auditive alert speaker were both connected to the control unit.

Figure 6 : Picture of the vibrotactile seat and the plan of the disposition of the mini vibrating motors on the seat cushion

Note. The left picture represents the vibrotactile seat in place. The right picture represents a schema of the vibrotactile seat with the position of the mini vibrating motors on it (blue dots).

Figure 7: *Picture of the mini vibrating motors with their shell*

Note. The shell on the left represents a closed shell with a mini vibrating motor inside, and the right shell represents the view inside.

A.1.4.2 Control units

The mini vibrating motors and the speaker were controlled via an Adafruit HUZZAH32 microcontroller (ESP32 Feather Board) to which other components were connected. For the tactile modality alerts control, a motor driver (Adafruit – DRV2605L) was used to control all the haptic motors. For the auditive alerts, a soundboard (Adafruit Audio FX Mini Sound Board) was used to upload the alert sound and play it as well as a stereo amplifier (Adafruit Adafruit TPA2016 2.8W) to control the speaker. To power this system, the microcontroller was connected via cable to the computer that was running the eye tracker software with a power of 3.2V. The system was connected to this specific computer because the live data from Smart Eye was used to set off the countermeasure. More precisely, when Smart Eye detects that the driver's gaze is off the screen for longer than the established threshold, it triggers the tactile and auditory alerts. This was made possible by a C++ code developed by the research team.

A1.5 Protocol

Participants were first greeted and then had to complete a consent form. Then they were installed in the simulator, and the seat was adjusted in such a way that participants were in an adequate driving position. Afterwards, the eye tracker was calibrated, and they were asked to complete a first questionnaire about their previous driving experience.

Participants then had a 15-minute familiarization task so they could get accustomed to the driving simulator. They were also shown how to properly use CarPlay so that all participants understood the basic operations of the IVIS for the interaction tasks. Before each of the tasks, participants were asked to maintain a constant speed between 50 and 60 km per hour regardless of any speed indication they would see during the simulation, and to follow the traffic code of the jurisdiction where this study took place. They were also informed that they will receive an auditory and vibrotactile alert in the CM1 and CM2 conditions without additional information. The three tasks (CM1, CM2, control) were each structured the same way, with the same order of interactions with the IVIS: *messaging-instruction, navigation, messaging-question, messaging-instruction, music, messaging-question, messaging-instruction, music, messaging-question*.

A1.6 Measures

To evaluate the effectiveness of the countermeasure in maintaining the driver's on-road visual attention, we looked at the distribution of the driver's gaze between on-road and off-road elements. Specifically, we measured the *off-road fixation rate*, which represents the proportion of time the driver's gaze was directed away from the road during each interaction, as well as the *off-road fixation time*, which is the amount of time the driver's gaze was directed away from the road during each interaction. We also measured the *number of triggered alerts* to assess if there was improvement in the visual attention to the road between the first and second time the driver drove with the countermeasure.

Additionally, we recorded the driving performance to assess the impacts of the countermeasure on road safety. Driving performance was indicated in two ways: 1) *the number of road violations* such as lane departures, failing to maintain a safe distance from the vehicle in front and collision with another solid object, and 2) *the speed and acceleration of the vehicle*. The first measure was collected automatically in the simulator software, and the second with additional software made by the research team calculated from simulator data.

We also used the NASA-TLX (Task Load Index) to assess the mental workload of the participant after each task. The NASA-TLX includes 6 subscales that measure the perceived 1) mental demand, 2) physical demand, 3) temporal demand, 4) performance, 5) effort and 6) frustration on a scale of 0 to 100 (Hart & Staveland, 1988). This measure was used to investigate the *perceived mental workload* after interacting with the IVIS while driving.

A1.7 Analysis

The analysis to assess the between-condition differences was performed for each dependent variable using RM ANOVA, with the participants' perceived CarPlay experience previous to the experiment and participants' years of experience with driving as a covariable. The significant threshold for all tests was set at $p \leq 0.05$, with a confidence level of 0.95. All analyses were conducted using "afex" and "emmeans" libraries of the R software (R core team, 2022).

A2 Results

The objective of the first experiment was to assess the efficacy of the eye-gaze-based countermeasure in re-directing drivers' visual attention back to the road and general driving performance. We hypothesize that driving with the countermeasure will increase on-road visual attention (H1.a), improve driving performance (H1.b) and result in lesser mental workload (H1.c) than driving without the countermeasure while interacting with an IVIS.

First, to verify the difficulty of the interactions with the IVIS, we examined the proportion of time drivers' visual attention was off-road while during each interactions. As we can see in **Table *4***, the proportion of time visual attention was spent off-road was as expected, with no IVIS interaction having the lowest proportion. Following by the low difficulty messaging, medium difficulty navigation, and high difficulty music interactions.

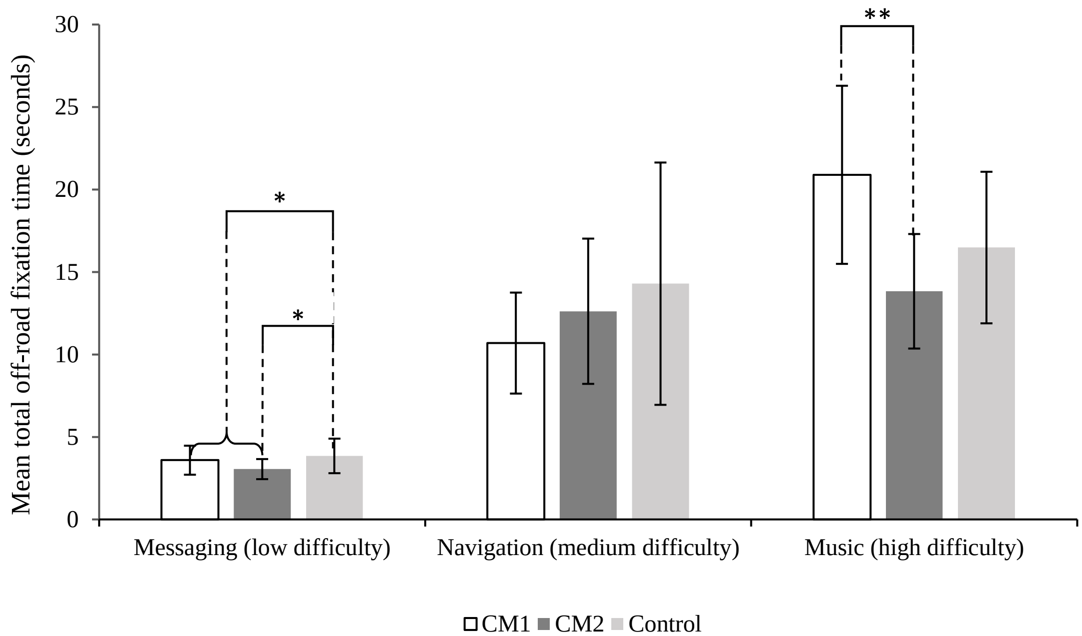
Table 4 : *Proportion of time spent visually off-road by participants for each type of interaction with the IVIS*

Interaction type	No interaction	Messaging	Navigation	Music
Proportion of time spend visually off-road	10,05%	14,48%	28,94%	41,85%

A2.1 On-road visual attention

The analysis of the off-road fixation time (**Figure 8**) shows a significant difference regarding the low complexity factor (i.e., messaging interaction). The contrast analysis shows a significant difference between the countermeasure and the control condition (estimated mean=0.54s, with a p-value of 0.028) as well as a significant difference between the condition where participants experienced the countermeasure for a second time and the control condition (estimated mean=0.81s, with a p-value of 0.023). This result shows that for the low complexity interaction, participants spent more fixation-time off-road when they were not driving with the countermeasure, and this difference increased when compared to the second time participants drove with the countermeasure.

Figure 8: *Mean total time in seconds where participants' glances were looking off-road for the different interactions' difficulties*

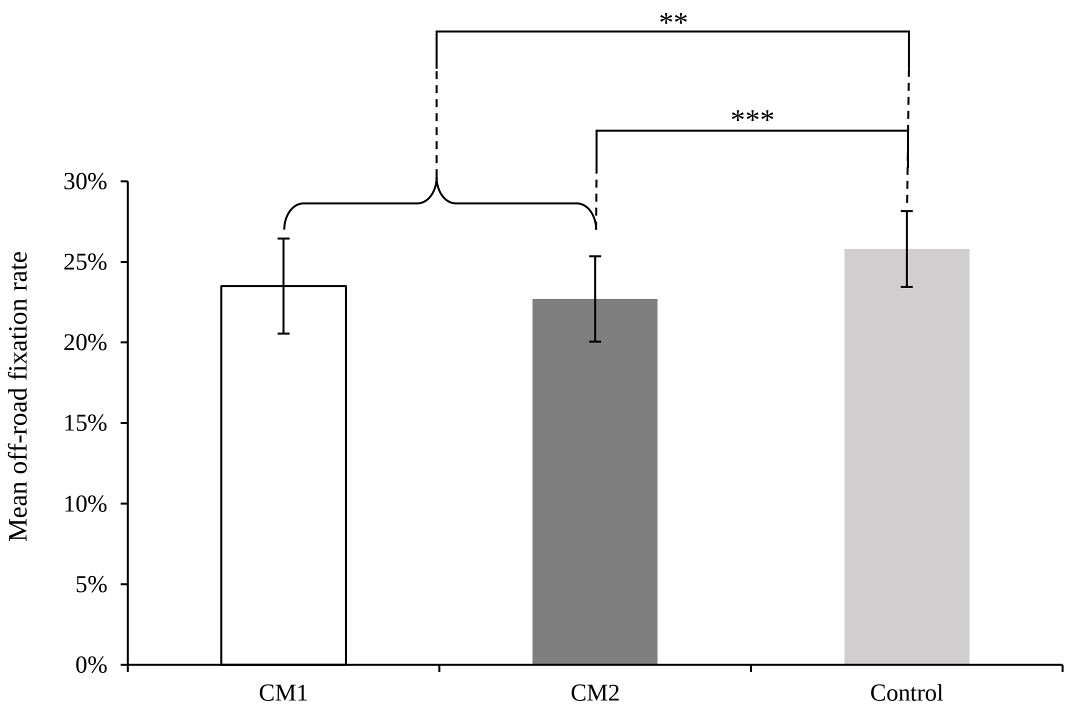


Note. *p < 0.05 and **p < 0.01

Moreover, in the music browsing interaction, there was also a significant difference between the first time and the second time participants experienced the countermeasure (estimated mean=7.06s, with a p-value of 0.012). This result indicates that for the high complexity interaction, participants spent less fixation-time off-road when they were driving with the countermeasure the second time in comparison to the first time they drove with the countermeasure.

Concerning the results for off-road fixation rate (**Figure 9**), there are significant differences between 1) both factors with the countermeasure and the control condition (estimated mean=2.70%, with a p-vale of 0.002), as well as 2) between the condition in which the participants experienced the countermeasure for a second time and the control condition (estimated mean=3.11%, with a p-value of 0.001). This result shows that a greater proportion of time was spent off-road when participants drove without the countermeasure, and this difference is higher when we consider only the second time they drove with the countermeasure.

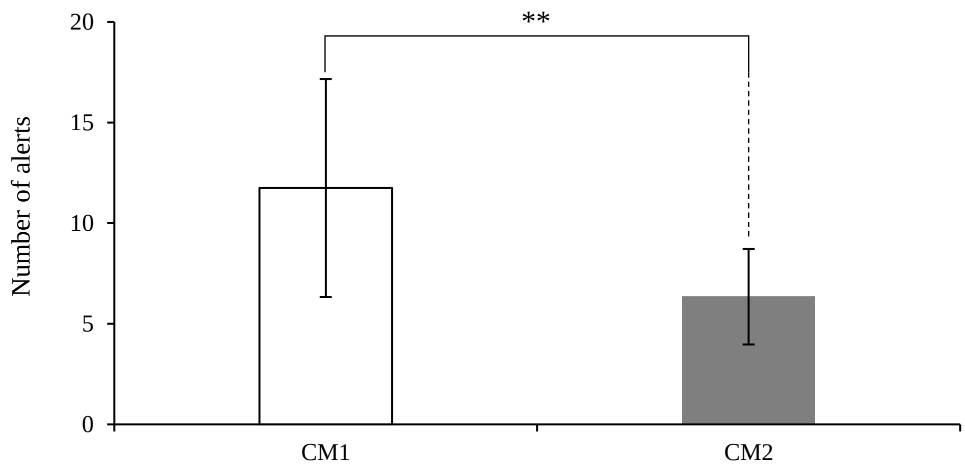
Figure 9: *Mean proportion of time participant had their gaze off-road during each conditions*



Note. **p < 0.01, *** and p < 0.001.

For the number of triggered alerts (**Figure *10***), there was a significant difference between the condition in which participants experienced the countermeasure for the first time and that in which participants experienced the countermeasure for the second time (estimated mean=5.4 activations, with a p-value of 0.008). This indicates that participants triggered the countermeasure's alert less when they drove with the countermeasure the second time compared to the first drive with the countermeasure, meaning they were adapting their behavior in order to avoid triggering alerts.

Figure 10 : *Comparison of the number of triggered alerts between the conditions where participants were experiencing the countermeasure for the first and second times*



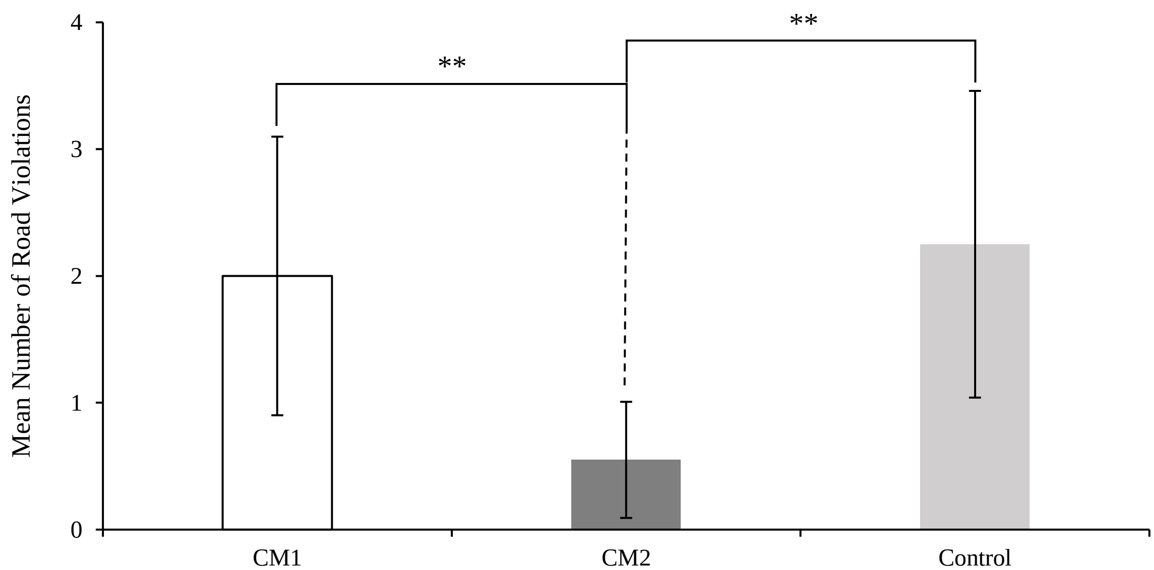
Notes. **p < 0.01

Off-road visual attention results show that the countermeasure was efficacious at raising SA by keeping participants' visual attention on the road more often, particularly the second time they drove with it, which supports the hypothesis H1.a that driving with the countermeasure will lead to greater on-road visual attention.

A2.2 Driving performance

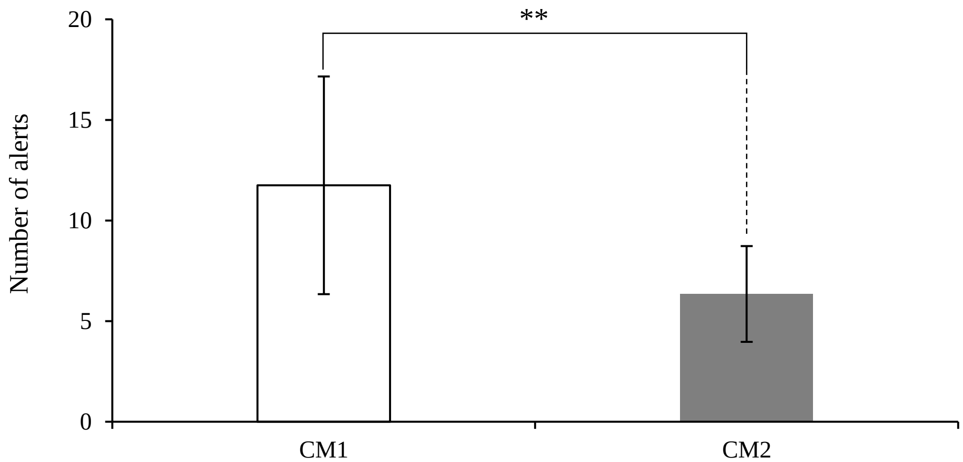
The analysis of the driving performance data shows no significant difference for the average speed variation and the average speed. However, it did have a significant difference for the number of road violations (**Figure 11**) between 1) the condition in which participants experienced the countermeasure for a second time and the control condition (estimated mean=1.70, with a p-value of 0.004), and 2) the condition in which participants experienced the countermeasure for the first time and that in which participants experienced the countermeasure for the second time (estimated mean=1.45, with a p-value of 0.010). These results show that participants had made fewer road violations when they drove with the countermeasure for the second time in comparison to when they did not drive with the countermeasure, as well as to when they were driving with the countermeasure for the first time. For the number of triggered alerts (**Figure 12**), there was a significant difference between the condition in which participants experienced the countermeasure for the first time and that in which participants experienced the countermeasure for the second time (estimated mean=5.4 activations, with a p-value of 0.008). This indicates that participants triggered the countermeasure's alert less when they were exposed to the countermeasure the second time compared to the first exposure to the countermeasure.

Figure 11: *Mean number of road violations during each condition*



Notes. **p < 0.01.

Figure 12: *Comparison of the number of triggered alerts between the conditions where participants were experiencing the countermeasure*



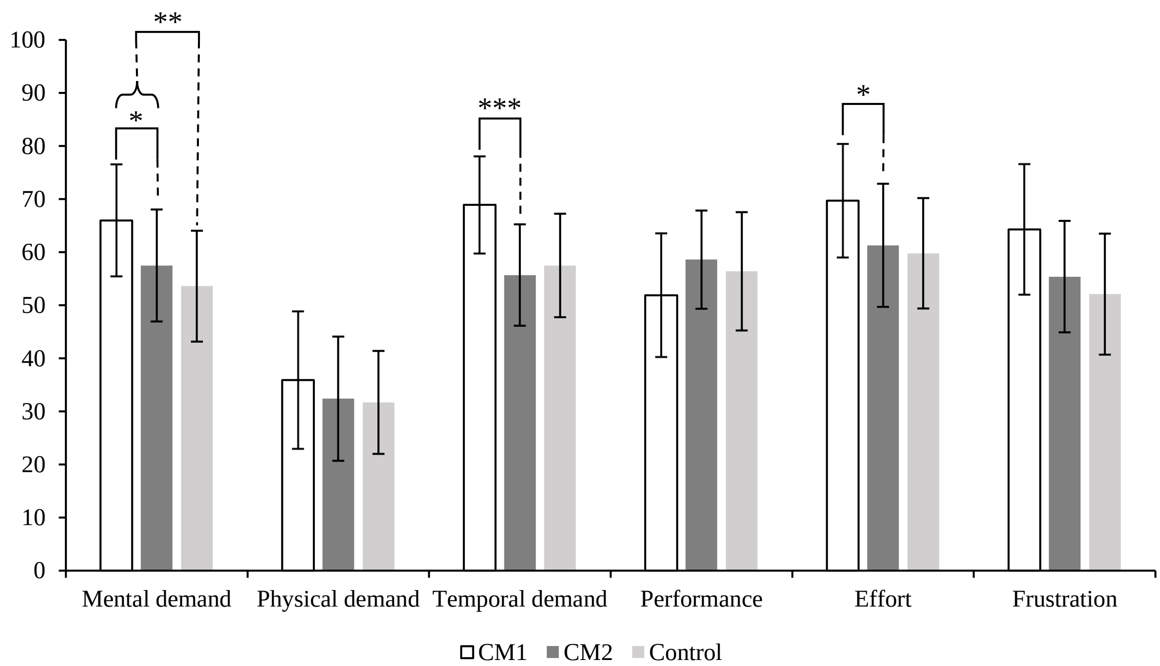
Notes. **p < 0.01

While the countermeasure greatly reduced the number of road violations they made, as well as the number of alerts triggered, they did not show significant difference in participants average speed and in speed variation. These results support hypothesis H1.b, that driving with the countermeasure will improve driving performance, showing that the presence of the countermeasure helps participants to make fewer road violations and trigger fewer alerts, thus improving road safety.

A2.3 Mental Workload

The RM ANOVA analyses on the NASA-TLX measures (**Figure 13**) reveal that there are significant differences between conditions in terms of mental demand, temporal demand, and effort, but that there are none in terms of physical demand, performance, and frustration.

Figure 13 : *Perceived workload during each condition*



Notes. *p < 0.05, **p < 0.01 and ***p < 0.001.

For mental demand, there were significant differences between 1) both conditions with the countermeasure and the control condition (estimated mean=-8.19, with a p-value of 0.007), as well as 2) the condition in which participants experienced the countermeasure for the first time and that in which participants experienced the countermeasure for the second time (estimated mean=8.57, with a p-value of 0.021). These results show that participants experienced lower mental demand when they drove without the countermeasure. However, this difference in mental demand was nonsignificant when they drove with the countermeasure the second time.

For temporal demand, there was a significant difference between the condition in which participants experienced the countermeasure for the first time and in which participants experienced the countermeasure for the second time (estimated mean=13.19, with a p-value of ≤ 0.001). This result indicates that participants experienced lower temporal demand when they drove with the countermeasure the second time in comparison to the first time.

Similarly, for effort, there was a significant difference between the condition in which participants experienced the countermeasure for the first time and that in which participants experienced the countermeasure for the second time (estimated mean=8.43, with a p-value of 0.018). This result indicates that participants experienced lower effort when they drove with the countermeasure the second time in comparison to the first time.

The hypothesis H1.c could not be supported because driving with the countermeasure did not reduce mental workload as compared to driving without the countermeasure. On the contrary, the mental demand was significantly higher when driving with the countermeasure the first time.

Table 5: *Summary of experiment 1 hypothesis*

Hypothesis	Prediction	Result
H1.a	Driving with the countermeasure will result **in increased on-road visual attention** during IVIS interactions, in comparison to driving without the countermeasure	Supported
H1.b	Driving with the countermeasure will result in **improve driving performance** during IVIS interactions, in comparison to driving without the countermeasure	Supported
H1.c	Driving with the countermeasure will result in **lesser workload** in comparison to driving without the countermeasure	Not supported

A3 Discussion

The objective of the experiment was to assess the effect of a countermeasure that uses eye-tracking to redirect a driver’s gaze on-road when they are distracted. The result of the present experiment shows that the negative effect of IVIS on visual attention and driving performance is reduced by the presence of the proposed countermeasure as expected. We can see that participants spend statistically more time on-road when experiencing the countermeasure, which supports hypothesis H1.a. For driving performance, participants made significantly less road violation the second time they drove with the countermeasure as compared to the first time they drove with it and without it, which is an improvement in driving performance. Therefore, we concluded that hypothesis H1.b is supported, even if results did not show significant differences in speed variation and average speed because the countermeasure improve driving performance through an increase in driver's visual attention on-road rather than through its speed performance. Hypothesis H1.c was not supported, and some findings suggest a relationship in the opposite direction with higher mental workload when driving with the countermeasure as compared to without it.

For off-road fixation time, there was no statistically significant differences when comparing the control and the countermeasure conditions for the moderate and high complexity interaction (navigation and music). This can be explained by the nature of the interactions. While most of the information necessary for messaging is communicated by the vocal assistant and via voice commands, this is not the case for music browsing and navigation interactions where drivers must read information available on the IVIS screen to complete their task. However, when considering the off-road fixation rate, we can see it is reduced for all the interaction types. While the reduction of the off-road fixation rate can be attributed to the reduction of the off-road fixation time for the messaging interaction, this is not the case for the navigation and music browsing interactions. The reduced off-road fixation rate in these two interactions with the non-significant difference in the off-road fixation time indicates that the drivers increased their time fixation on the road during the beginning and end of their interactions with the IVIS screen in the countermeasures conditions. In other words, the interactions with the IVIS screen to look for specific music or to find a specific address were visually more complex and needed a certain amount of visual attention to be achieved. The countermeasure did not decrease the time spent visually off-road, but instead increase the time spent visually on-road between glances, thus lowering the off-road fixation rate for those interactions.

Data also seem to show that participants were better the second time they drove with the countermeasure as compared to the first time. This seems to be the case for the number of road violations and for the number of triggered alerts where participants performed significantly better the second time driving with the countermeasure as compared to the first time. This can be explained by a habituation effect to the countermeasure, where participants were more comfortable and accustomed to the countermeasure the second time they drove with it. Moreover, this effect can explain why there is a statistically significant difference in the off-road fixation time for the more complex interactions (music) between the first and second time driving with the countermeasure. The participants' habituation to the countermeasure prompted them to adapt their behavior, as they endeavored to minimize instances of alerts activation during their engagement with the IVIS. Thereby reducing their off-road fixation time when their gaze was directed toward the IVIS. Finally, the NASA-TLX data is also in line with the idea of a habituation effect, showing that the workload was significantly greater the first time participants drove with the countermeasure when compared to the second time for the mental, temporal and effort dimensions. In line with Kujala et al. (2016), the findings suggest that a physiological-based countermeasure can help drivers increase their on-road visual attention while engaged in non-driving-related tasks.

B. Experiment 2

B1 Methodology

Experiment 2 was design in order to test hypotheses 2 and 3 (H2.a, H2.b, H3.a and H3.b), exploring the research question: which combination between auditory, tactile and visual modalities is the most effective in redirecting driver's visual attention from an IVIS to the road?

The second experiment presented in this study was conducted with the same simulator as the first experiment. Thus, the instrument, the apparatus, the protocol and the measures were the same.

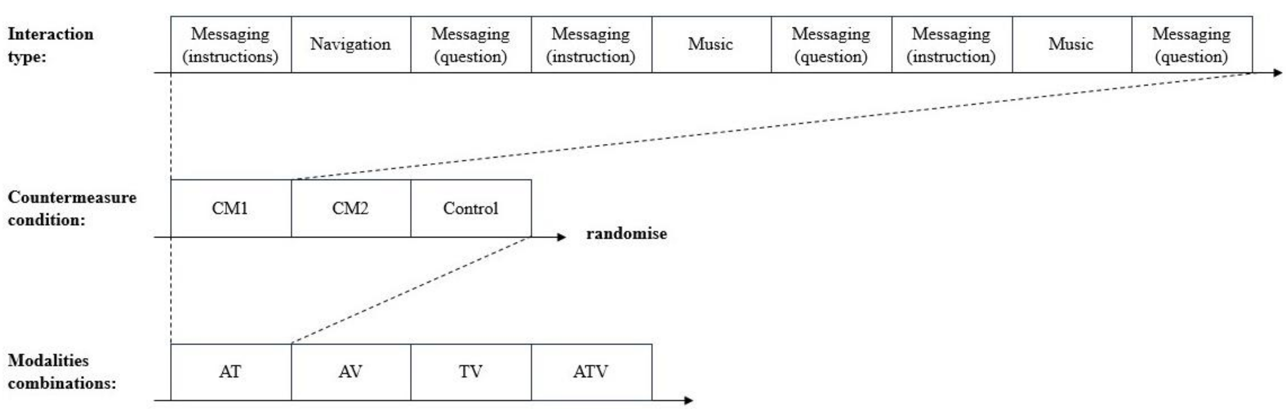
B1.1 Participants

Fifty-one participants were recruited via a research panel, with 25 who identified themselves as male and 26 as female, between the ages of 19 and 47 (mean = 26.75 and SD = 6.46). All participants had to be 18 years old, have a valid driver's license in our jurisdiction (the simulator in this study uses the traffic code of this jurisdiction), wear appropriate footwear, not be susceptible to certain conditions (motion sickness, epilepsy, or skin allergies), or require glasses to drive. At the end of the study, each participant received a compensation of $30 for their participation.

B1.2 Experimental design

This study used a three-factor design, with the type of alert as between-subjects and the exposure to the countermeasure as well as the difficulty of interaction as within-subjects (see **Figure** ***14***). The first factor was the type of alert with four levels: 1-auditory-tactile (AT), 2-auditory-visual (AV), 3-tactile-visual (TV), and 4-auditory-tactile-visual (ATV). As in Experiment 1, the experimental session consisted of driving the same road three times, twice with the countermeasure and once for the control condition (CM1, CM2, Control) (see **Table 2**). Finally, the third factor was the difficulty of the interaction, which was also the same as in experiment 1 (Messaging-Question, Messaging-Instruction, Navigation and Music) (see **Table 3**).

Figure 14: *Experimental protocol of the second experiment*



B1.3 Countermeasure design

To answer the second research question, a visual alert was added to the control unit of the countermeasure.

The visual alert consisted of a 300mm LED stripe (Adafruit NeoPixel) that was placed on top of the speaker and was visually on top of the steering wheel. The color red was used to communicate urgency. Moreover, the visual alert was connected directly to the control unit.

B1.4 Analysis

In order to analyse the efficacy of the alerts modalities, we used a mixed-model ANOVA with the same covariables as in experiment 1. The significant threshold for all tests was set at $p \leq 0.05$, with a confidence level of 0.95. All analyses were conducted using "afex" and "emmeans" libraries of the R software (R core team, 2022).

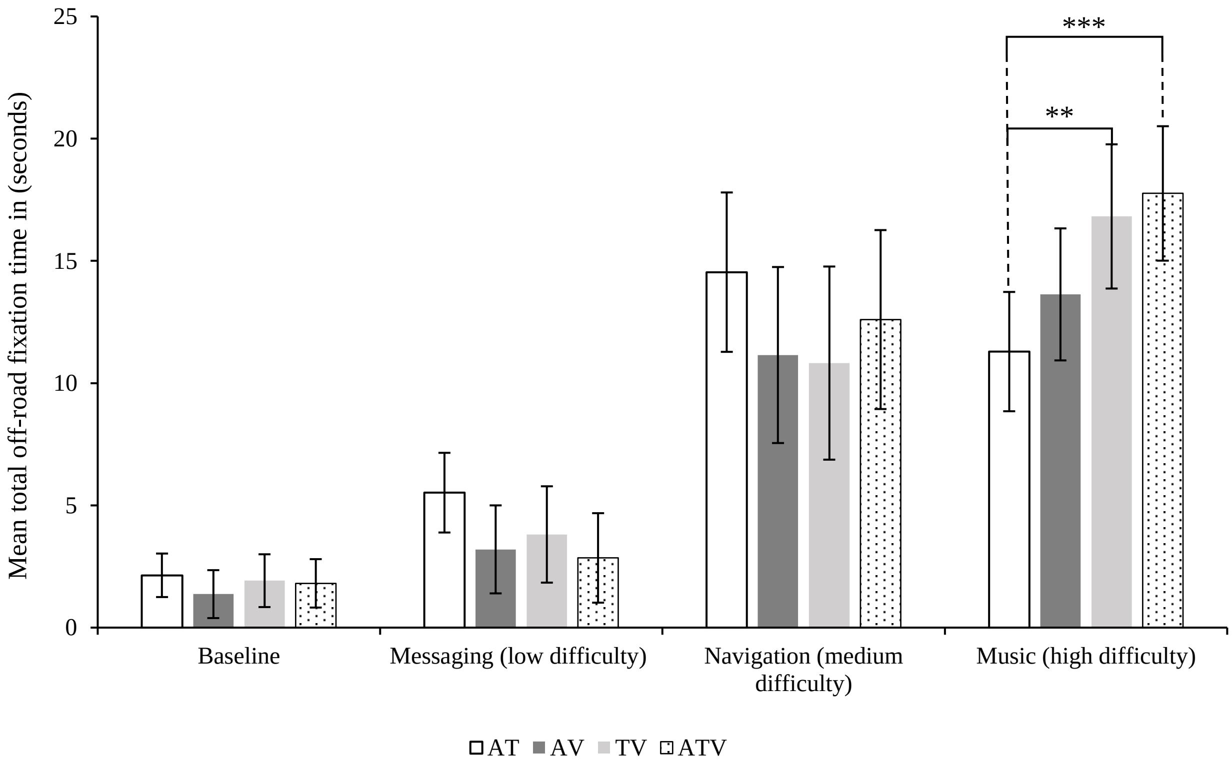
B2 Results

The objective of the second experiment was to assess the efficacity of different modality combinations to determine their effect on the proposed eye-gaze-based countermeasure. We hypothesize that bimodal combination with the visual modality will be less effective at increasing on-road visual attention (H2.a) as well as less effective at improving driving performance (H2.b) while interacting with an IVIS. We also hypothesize that the trimodal combination will be more effective than the bimodal combinations at increasing on-road visual attention (H3.a) and more effective at improving driving performance (H3.b) while interacting with an IVIS. This result section will first describe the results in line with our second set of hypotheses (H2), then our third set of hypotheses (H3).

B2.1 On-road visual attention

The analysis of off-road fixation time (**Figure 15**) shows a significant difference during the high complexity interaction between 1) the AT and ATV conditions (estimated mean=-6.48 with a p-value=0.0057) as well as 2) the AT and TV conditions (estimated mean=-5.53 with a p-value=0.0272). The p-value was adjusted using the Tukey method for comparing a family of 4 estimates. These results indicate that during the high complexity interaction, participants spent significatively less time looking away from the road with the auditory-tactile modality. However, the difference was not significant in the auditory-visual condition. The analysis of off-road fixation rate did not reveal significant results. Interactions' difficulties consider the average of cm1 and cm2 for each modalities' combinations.

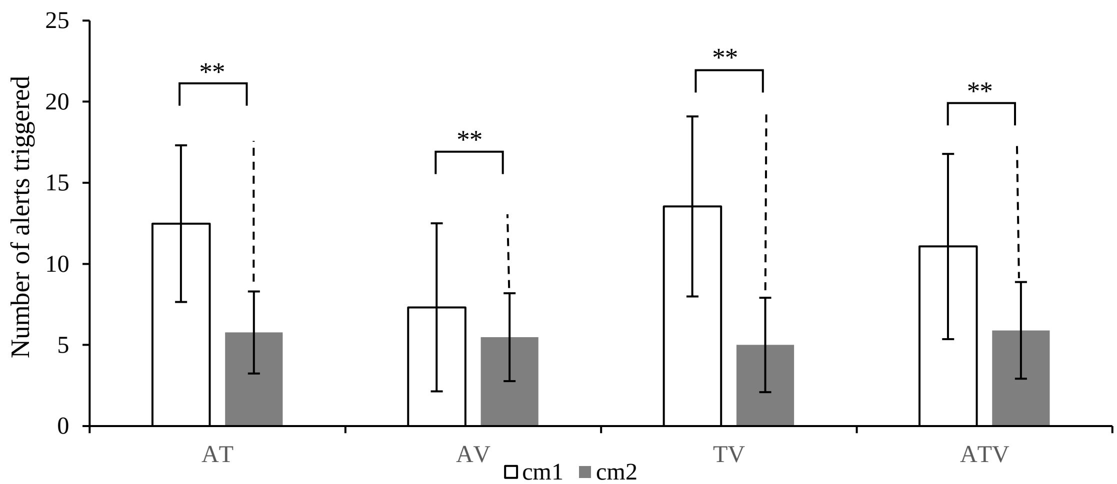
Figure 15: *Mean total time in seconds where participants glances were looking off-road for the different interactions' difficulties*



Notes. **p < 0.01 and ***p < 0.001. AT = auditory-tactile, AV = auditory-visual, TV = tactile-visual, ATV = auditory-visual-tactile.

We also analyse the number of triggered alerts (**Figure 16:** Comparison of the number of triggered alerts between modality combinations) when the participants drove with the countermeasure. First, this data shows that participants triggered more alerts the first time they drove with the countermeasure as compared to the second time. This result shows that there was a learning effect on the participants the second time they drove with the countermeasure as in experiment 1. However, there were no significant differences in the number of alerts between the different combinations. This absence of significant differences between the bimodal combinations with and without the visual modality and between bimodal and the trimodal combinations suggests that there might not be differences in preventing the user's attention from leaving the road before the established threshold, i.e., before the alert is triggered.

Figure 16: *Comparison of the number of triggered alerts between modality combinations*



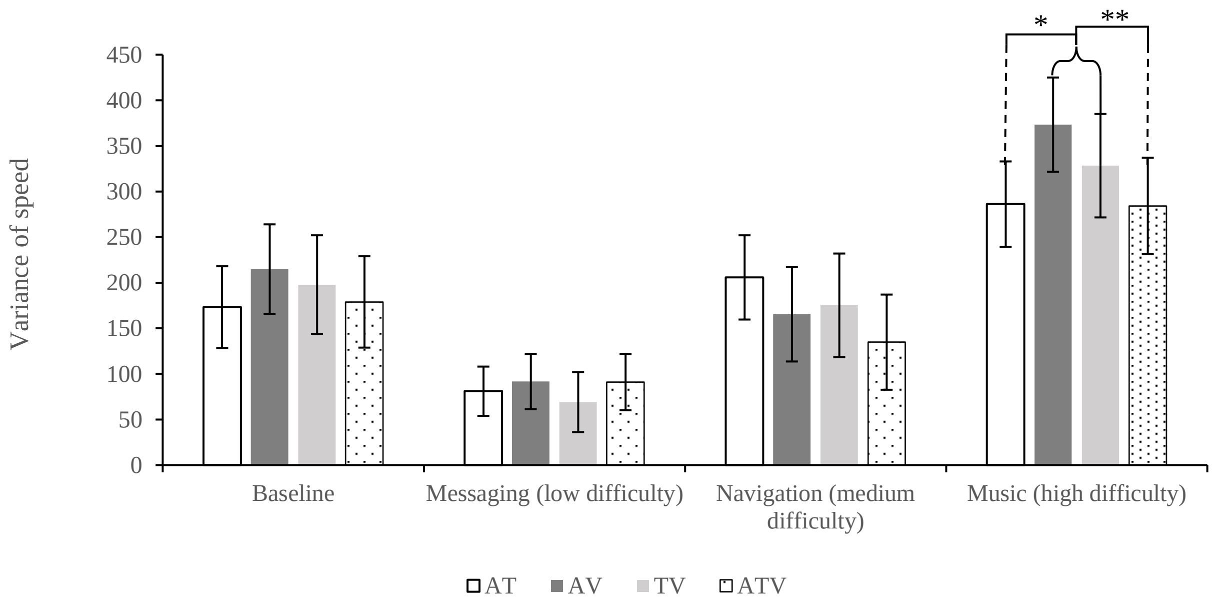
Notes. **p < 0.01.

Concerning the modalities' efficacity, the results show that bimodal alerts with a visual component are less effective than the auditory-tactile modality for redirecting drivers' visual attention to the road (H2.a), but only during a high complexity interaction with an IVIS. However, for H3.a, results do not show that trimodal alerts are more effective than bimodal ones. Specifically, they show that the AT alerts seem to perform as well in number of triggered than the ATV alerts, but better for the off-road fixation time.

B2.2 Driving performance

In the analysis of the average speed variation (**Figure 17**), results reveal significant differences between 1) AT and the other bimodal conditions (mean of AV and TV) (estimated mean=-64.7 $(km/h)^2$, with a p-value of 0.0380) for the high complexity interactions and 2) when comparing ATV condition with the other two bimodal conditions (mean of AV+TV) (estimate mean=-66.7 $(km/h)^2$, with a p-value of 0.0147) also for the high complexity interaction. These results show that bimodal combinations with a visual alert had a higher average speed variation than other combinations. Concerning the average speed, the ANOVA did not show significant results. Interactions' difficulties consider the average of cm1 and cm2 for each modalities' combinations.

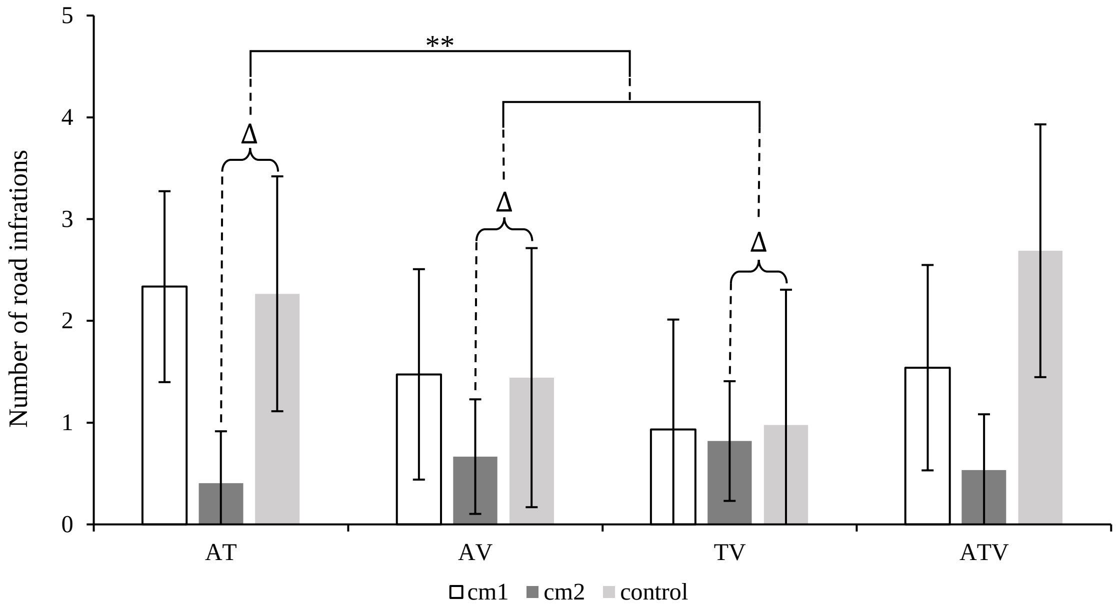
Figure 17: *Average speed variation for the different interactions' difficulties*



Notes. *p < 0.05 and **p < 0.01.

In addition, no statistically significant differences were observed during the driver's second exposure to the countermeasure in terms of number of road violations (**Figure 18Error! Reference source not found.**). However, further analysis of the number of road violations when accounting for the control condition, specifically when comparing the differences in the number of road violations relatively to the control condition in the AT condition compared to both the AV and TV conditions, the AT condition significantly reduced the number of road violation in reference to their control conditions (estimated mean = -0.77 infractions, with a p-value of 0.012).

Figure 18: *Mean number of road violations for each modality combination*



Notes. **p < 0.01.

The results support our second hypothesis that bimodal countermeasures including visual alerts are less effective at improving driving performance than the AT condition (H2b), but do not support the third hypothesis that the trimodal countermeasure will be more effective at improving driving performance all bimodal countermeasures (H3b).

Table 6: *Summary of experiment 2 hypothes*is

Hypothesis	Prediction	Result
H2.a	Bimodal combination incorporating the visual modality will be less effective **at increasing on-road visual attention** during IVIS interactions, in comparison to the bimodal combination with only auditory-tactile modalities.	Supported
H2.b	Bimodal combination incorporating the visual modality will be less effective **at improving driving performance** during IVIS interactions, in comparison to the bimodal combination with only auditory-tactile modalities.	Supported

H3.a	Trimodal combination will be more effective than all bimodal combinations at **increasing on-road visual attention** during IVIS interactions.	Not supported
H3.b	Trimodal combination will be more effective than all bimodal combinations at **improving the driving performance** during IVIS interactions.	Not supported

B3 Discussion

The objective of this experiment was to assess the effectiveness of three different modalities in bimodal and trimodal combinations for the eye-gaze-based countermeasure. It was hypothesized that bimodal combinations with the visual modality would be less effective at increasing on-road visual attention (H2.a) and improving driving performance (H2.b) because of the high visual demand of the driving activities. We also hypothesized that the trimodal combination will be more effective than all bimodal combinations at increasing on-road visual attention (H3.a) and improving driving performance (H3.b) due to previous studies on trimodal alerts. Our results support H2, in both on-road visual attention and driving performances. However, they do not support either of the hypotheses for H3 (H3.a and H3.b).

The results show, as expected, that bimodal combinations with the visual modality were less effective at redirecting drivers' visual attention and less effective at increasing driving performance. Participants were spending significantly less time off-screen in the AT condition as compared to the other bimodal and trimodal combinations for the high complexity interaction (music). Moreover, the AT and ATV conditions had lower speed variation than the other bimodal combinations. For the number of road violations and alerts triggered, we can observe the same results, which is a significant difference the second time participants drove with the countermeasure between the AT condition and both the AV and TV conditions.

Results demonstrate for the number of triggered alerts and the average speed variation that the AT combinations was as effective than the ATV combinations, which is in line with Lundqvist & Eriksson (2019) et Politis et al. (2014) where the authors did not found significant differences between AT and ATV combinations. However, results for the off-road fixation time and number of road violation show that the AT combinations was more effective than the ATV combinations. These results are unexpected because the trimodal combination was hypothesis to be more effective than all the bimodal combinations, as in Huang et al. (2019 Huang & Pitts (2020).

Overall, the second experiment suggests that combinations with the visual modality is less effective at redirecting drivers' attention on-road as compared to the combination with only the auditive and tactile modalities. Moreover, the trimodal combination does not seem to be significantly better than any of the bimodal combinations.

3. General discussion

The main results of experiment 1 and 2 show, as expected, that the presence of the eye-gaze-based countermeasure was effective at redirecting driver's visual attention away from the IVIS and back to the road and improving driving performance when participants drove with the countermeasure the second time. As for the bimodal combinations, the results also show as expected that bimodal combinations with a visual component would be less effective than the auditory-tactile combination. However, surprisingly the trimodal combination was not more effective than all bimodal combinations as there was no significant difference between the trimodal and the auditory-tactile combinations.

This can be explained by the fact that since vision is extremely important in the context of driving. When presenting a visual alert, the alert itself requires the driver to look away from the road to notice the alert and thus diminishes its effectiveness. This can be attributed to the inherent limitations of human in multitasking, as presented by Wickens (2008), whereby tasks demanding concurrent engagement of the same sensory inputs tend to exhibit compromised performance. Consequently, the supplementation of visual input to the audio and tactile modalities in the context of the trimodal combination does not confer any additional value as an alert.

The effectiveness of the eye-gaze-based countermeasure goes beyond redirecting of the visual attention to the road and also affects the performance of the drivers as reflected in the number of traffic violations committed. This difference in the number of violations was significant the second time participants experienced countermeasure. This points towards a relatively fast learning effect, as the participants adapted to the alerts associated with countermeasures and thus changed their behavioral patterns accordingly. This is in line with Dingus et al. (2006), Horrey & Wickens (2007), and Liang et al., (2014), as our results showed fewer road violations when the driver had their gaze redirected after a 1.6-second threshold and when they were more familiar with the countermeasure. However, it is important to note that implementing a static threshold is contested because the amount of time looking away from the road is not the only factor responsible for accidents, and it is possible for them to occur within the 1.6-second threshold. Drivers must be aware of their environment and choices of when to interact with an IVIS should depend on the demands of the driving situation and their capacity to engage in a non-driving related task.

One interesting finding when comparing the first and second exposure to the countermeasure is that participants adjusted their behavior such that a lower number of alerts were triggered the second time. Instead of redirecting their gaze to the road after the alert was triggered, participants took an anticipatory approach: they had become familiar with the amount of time it took to trigger the alert and tried to redirect their attention to the road before the alert was triggered. This shows a change of behavior not directly related to the alert of the countermeasure but merely to the presence of countermeasure itself. It also suggests that having a static threshold might be useful as it's consistent timing encourages learning and adaptation.

The relevance of this countermeasure in vehicle is not only for preventing drivers' distractions, but also for acting as a safeguard for when technologies like ADAS don't act properly as reliability issues has been raises concerning those systems (Amditis et al., 2005; Kiefer et al., 2005). Drivers that put too much trust in these systems could face unintended consequences. This also raise legal concern as drivers are legally expected to have a safe driving behavior, but the human factor should be taken into account, and the involvement of these systems in accidents must be acknowledge.

4. Conclusion

This study advances a new eye-gaze-based countermeasure to reduce drivers' distraction while driving and finds support for its use. The use of an auditive and tactile alert when drivers' gaze off-road exceeds 1.6 seconds leads to more time spent visually on-road as well as fewer road violations when drivers are interacting with an IVIS. This suggests that a countermeasure reacting directly to a driver's inattention instead of reacting to a driver's mistakes resulting from inattention can be a way to enhance road safety.

Furthermore, the countermeasure seems to have a learning effect on participants when they attempt to avoid triggering the alerts. It appears that their behavior was centered around trying to prevent the alert rather than reacting to it.

This study also contributes by showing the potential application of eye-tracking technologies in vehicles that assess drivers' visual attention in real time, allowing the countermeasure to prevent the effects of distraction before they occur. The study's results advocate using eye tracking technologies to help reduce drivers' distraction as a potentially useful and effective addition to in-vehicle technologies, thus necessitating further investigation by researchers and car manufacturers. Actual studies on the integration of eye tracking are about real-time assessment of the driver state and to what extent of reliability they can assess it (Hecht et al., 2019a). The present study goes a step further in the implementation of eye-tracking technology in-vehicle by providing an example of real-time data application in a driving context, as in Kujala et al. (2016).

The proposed eye-tracking-based countermeasure enhances road safety and limits the impact of distractions. As such, policy makers can introduce new regulations for car manufacturers around the implementation of similar systems in new vehicles to mitigate increasing IVIS distractions. While actual distraction mitigation systems are about reducing the distraction potential from an IVIS interface and reacting to distracted drivers' mistakes with ADAS, similar countermeasures that prevent distractions could be considered as an additional and potentially more effective layer to be integrated into in-vehicle technologies to mitigate driver distraction.

This study offers multiple ideas for future research such as further investigate drivers' trust in and annoyance with this countermeasure, as it is linked to the adoption or dismissal of it (Bliss & Acton, 2003; Kiefer et al., 1999). The learning effect and the different behavioral adaptations of drivers using the countermeasure presented could be re-examined to determine the extent of their influence. Further research is also needed to test the effectiveness of the countermeasure in a more ecologically valid environment.

Moreover, the results in the second experiment did not suggest that there is an enhancement effect from the trimodal combination when compared to the auditive-tactile combination. This is in line with some studies (Lundqvist & Eriksson, 2019; Politis et al., 2014) and in contradiction with some others (Huang et al., 2019; Huang & Pitts, 2020). It is difficult to point out why those results occurred due to the variance in the presentation characteristics of the visual modality and the divergence in the experimental protocols across these studies. However, the studies that reported the presence of an enhancement effect with trimodal over bimodal combinations were conducted within the context of semi-autonomous driving. This raises the possibility that such augmentation effects might be discernible within semi-autonomous driving circumstances. Therefore, the enhancement effect of trimodal alerts (auditory-tactile-visual) in comparison to the auditory-tactile combination should be investigated further in a driving context and compared to a semi-autonomous driving context.

A limitation of this study is that the proposed eye-gaze-based countermeasure did not consider the driving environment such as participants' speed, road condition or the position of others car around as in Kujala et al. (2016). Future research should examine more the effects of taking into account the driving environment in and adjusting the alert threshold. Thus, in a high road-demand context (high-density traffic, fast speed, many turns, etc.) the threshold could be lower, and in a low road-demand context (low-density highway, the vehicle is immobilized, etc.), it could be higher. Such consideration could potentially improve both on-road security and driver acceptance of the countermeasure.

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Conclusion

Le travail présenté dans ce mémoire répondait à plusieurs objectifs. Pour répondre à ceux-ci, deux questions de recherches ont été élaborées. Une première expérimentation fut réalisée afin de répondre à la question suivante: dans quelle mesure une contre-mesure qui prend en considération le regard d'un conducteur est-elle efficiente à rediriger l'attention visuelle d'un conducteur d'un SIE à la route ? Une seconde expérimentation a été menée afin de répondre à la question : laquelle des combinaisons entre les modalités auditive, tactile et visuelle est la plus efficace pour aider la contre-mesure à rediriger l'attention visuelle d'un conducteur d'une SIE à la route? Ce second objectif vise à tester différentes combinaisons de modalité afin de déterminer laquelle contribue de manière plus efficace comme alerte à la contre-mesure proposée. Les modalités à l'étude étaient les suivantes : auditive, tactile et visuel dans leurs combinaisons bimodales (auditive-tactile, auditive-visuelle et tactile-visuelle) et trimodale (auditive-tactile-visuelle).

Les données récoltées lors de la première expérimentation ont révélé de nombreuses informations intéressantes. Premièrement, conformément aux attentes, l'utilisation d'une contre-mesure pour rediriger l'attention visuelle d'un conducteur lorsque son regard hors route dépasse un seuil de 1,6s. augmente l'attention visuelle sur la route lors d'interaction avec un SIE. Ces résultats suggèrent qu'une contre-mesure réagissant à l'inattention d'un conducteur plutôt qu'aux conséquences de celle-ci peut être considérée comme un moyen d'améliorer la sécurité routière. Deuxièmement, même si la contre-mesure améliore les performances de conduites, celle-ci n'améliore pas les performances de vitesses. Ainsi, la contre-mesure améliore les performances de conduite à travers une l'augmentation de l'attention visuelle du conducteur. Troisièmement, à la différence de ce qui était anticipé, la présence de la contre-mesure lors de la conduite n'a pas réduit la charge mentale du conducteur, mais n'est pas statistiquement significative lorsque comparée à la deuxième fois où les conducteurs étaient exposés à celle-ci. Les données de cette expérimentation démontrent un effet d'accoutumance envers la contre-mesure ou les résultats sont significativement meilleurs entre la première et la deuxième fois que les conducteurs conduisent avec celle-ci. Ainsi, il serait intéressant de vérifier les résultats sur la charge mentale avec des conducteurs plus accoutumés à cette dernière.

Pour ce qui est des données récoltées lors de la deuxième expérimentation, conformément à ce qui était attendu, les combinaisons bimodales comprenant la modalité visuelle étaient moins performantes à rediriger l'attention visuelle sur la route et à améliorer les performances de conduites lors d'interactions avec un SIE. Ces résultats suggèrent que la modalité visuelle n'est pas aussi efficace à alerter un conducteur que les autres modalités et de ce fait, entre en concurrence avec la demande visuelle de la conduite. Deuxièmement, contrairement à ce qui était envisagé, la combinaison trimodale n'était pas plus performante à rediriger l'attention visuelle sur la route et à améliorer les performances de conduites lors d'interactions avec un SIE. Ce résultat étonnant démontre que pour l'attention visuelle sur la route, la combinaison trimodale était moins performante que la meilleure combinaison bimodale (auditive-tactile). Cependant, pour ce qui est des performances de conduite, la combinaison trimodal semblait aussi bien performer que la meilleure combinaison bimodale. Il est possible que la modalité visuelle ait pu influencer négativement l'attention visuelle des conducteurs sur la route, mais pas les performances de conduites. Ce phénomène mériterait d'être plus approfondi afin de mieux comprendre les raisons derrière ces résultats. Les résultats de cette deuxième expérimentation suggèrent fortement que la combinaison bimodale auditive-tactile est une alerte viable et efficace à utiliser pour rediriger l'attention d'un conducteur distrait. Pour ce qui est de l'alerte trimodale, davantage de résultats empiriques devraient être amassés avant de pouvoir attester de la viabilité et de l'efficacité de cette combinaison.

Ce mémoire apporte une contribution significative en démontrant l'efficacité d'une contre-mesure qui prend en considération le regard du conducteur à limiter les impacts de la distraction au volant et ainsi améliorer la sécurité routière. Dans un premier temps, les résultats obtenus peuvent inciter les décideurs politiques à implémenter de nouvelles régulations visant les manufacturiers automobiles à implémenter des solutions similaires afin de faire face à la distraction au volant causée par les SIE pendant la conduite. De plus, les systèmes comme les SSEC et les SAC présents dans les véhicules ont des lacunes : les SSEC alertent les conducteurs lorsque son état n'est plus propice à la conduite sécuritaire, sans toutefois prendre des mesures pour limiter ou prévenir ce changement d'état, et les SAC demandent à un conducteur distrait de réagir aux conséquences de sa distraction, ils constituent davantage une solution de dernier recours plutôt d'un moyen proactif d'éviter les accidents. La contre-mesure proposée dans ce mémoire vient compléter ces systèmes existants en ajoutant une mesure préventive supplémentaire qui intervient au moment même de la distraction. Dans un second temps, cette étude démontre également l'application potentielle des technologies d'oculométrie dans les véhicules, permettant d'évaluer en temps réel l'attention visuelle du conducteur afin de prévenir les effets de la distraction avant qu'ils ne surviennent. Les résultats de l'étude indiquent que l'utilisation des technologies de suivi oculaire pour surveiller l'état du conducteur, dans le but de réduire la distraction lors des interactions avec un SIE, constitue un complément utile et efficace aux technologies embarquées, nécessitant ainsi des recherches plus approfondies de la part des chercheurs et des constructeurs automobiles. Finalement, les résultats de ce mémoire contribuent à la littérature scientifique en apportant une réponse supplémentaire à l'incertitude qui entoure l'existence d'un effet d'amélioration entre les combinaisons bimodales et trimodale dans le cadre d'études expérimentales et en contexte de simulations de conduite. Alors que cet effet a été prouvé, son existence en contexte de conduite était incertaine. Ainsi, dans le contexte expérimental présent, nous n'avons pas pu démontrer la présence d'un tel effet. Bien que ces résultats ne suffisent pas à confirmer ou infirmer cette incertitude, ils contribuent en apportant une preuve supplémentaire. Une limite de cette étude est le réalisme de son simulateur. Une solution possible pour de prochaines expérimentations serait un partenariat avec un manufacturier automobile puisque plusieurs d'entre eux possèdent des simulateurs hautement réalistes.

Ce mémoire présente le design et la conception préliminaire d'un nouveau type de contre-mesure utilisant les données oculométriques d'un conducteur pour prévenir la distraction. Par conséquent, le travail réalisé dans cet ouvrage est préliminaire et nécessite des efforts supplémentaires afin de déterminer le réel impact et utilité de cette contre-mesure. Davantage de travail devra aussi être mis afin d'améliorer le design de celle-ci dans le but d'en augmenter son efficacité. À cette fin, plusieurs participants ont fait la remarque que parfois, les alertes se sont déclenchée dans des situations où ils auraient pu passer plus de temps à regarder en dehors de la route due à la faible demande de celle-ci à ce moment.

Dû à des limitations de temps, ce mémoire n'a pas tenu compte de l'environnement du conducteur, mais cet ajout pourrait s'avérer pertinent pour l'acceptabilité du système par les conducteurs. L'étude de Kujala et al. (2016) peut servir d'une bonne base de départ à cette fin. Ensuite, étant donné qu'un système efficace est avant tout un système que les utilisateurs utilisent, l'appréciation et la confiance envers le système devraient être de prochains facteurs mesurés dans de futures expérimentations. De plus, telle que développée dans le paragraphe précédent, l'incertitude envers l'effet d'amélioration présent entre la combinaison bimodale auditive-tactile et trimodale devrait être davantage étudiée en contexte de conduite. Je souhaite souligner aux futurs étudiants intéressés et curieux du domaine de l'automobile que l'expérience utilisateur à bord des véhicules est et sera un enjeu important et stratégique pour les fabricants automobiles.

Pour conclure, la contre-mesure présentée dans ce mémoire est efficace à rediriger l'attention visuelle des conducteurs sur la route. De plus, bien que la contre-mesure n'améliore pas les performances de conduites, il a été observé qu'après une première exposition à la contre-mesure, les participants adaptaient leur comportement de manière à ne plus déclencher d'alerte, ce qui a mené a significativement moins d'alertes déclenchées et moins d'infractions routières lors de leur deuxième conduite avec la contre-mesure. Pour ce qui est des modalités utilisées dans les alertes et leur combinaison bimodales, il a été observé que les combinaisons comprenant la modalité visuelle étaient moins performantes. Pour ce qui est de la combinaison trimodale, il a été observé que cette dernière n'était pas plus performante que la meilleure combinaison bimodale (auditive-tactile) pour ce qui est de l'attention visuelle sur la route, mais performait de manière semblable pour les performances de conduite. De ce fait, les résultats suggèrent que la combinaison auditive-tactile contribue de manière la plus efficace à la contre-mesure proposée.

Les résultats de cette étude démontrent que l'utilisation de la contre-mesure proposée dans ce mémoire améliore la sécurité routière dans un contexte de conduite en simulateur. L'implication de la distraction due à des tâches non essentielles à la conduite dans les accidents est un phénomène important qui représente plus de la moitié des accidents (Dingus et al., 2016). L'interaction avec des technologies comme les systèmes d'infodivertissement embarqué et l'utilisation de téléphone intelligent sont des facteurs importants de cette distraction (Horrey & Wickens, 2006; Lee et al., 2004a; McKnight & McKnight, 1993; Ramnath et al., 2020; Strayer et al., 2006; Strayer, Cooper, Goethe, et al., 2017; Strayer, Cooper, Turrill, et al., 2017). Avec l'arrivée de la conduite autonome et la place grandissante de la technologie dans les véhicules, les distractions vont aussi croitre. Ainsi, des systèmes préventifs, comme celui présenté dans ce mémoire, doivent être désignés et évalués afin de pouvoir être implantés au sein de véhicules. La distraction est un enjeu actuel et futur sérieux pour la sécurité routière et des mesures doivent être prise afin d'en limiter les impacts.

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Annexes A

Cette annexe consiste en un article écrit en septembre 2022 en lien avec ce mémoire. Cet article a été rédigé afin d'être envoyé à CHI 2023 et porte sur la première expérimentation réaliser dans le cadre de ce mémoire. Malheureusement l'article c'est vue refusé par les réviseurs, mais les commentaires émit ont été constructif et pertinent. Ceux-ci ont été pris en compte en intégrer dans l'article présenté au Chapitre 2.

1 INTRODUCTION

Driving while being distracted is a risky behavior that results in major social and economic costs. In 2020, the number of fatalities related to distracted driving was 3142 in the United States (Stewart, 2022). In Europe, distracted driving accounted for 5 to 25% of all crashes (Hurts et al., 2011) and in 2017 accounted for 25.3% of all road fatalities in Canada (Brown et al., 2021). Because people do not always reveal they were distracted when they are involved in an accident, it is difficult for police reports to assess the true extent of driver distraction. However, naturalistic driving data analysis of causal factors leading to crashes shows that 68.3% of these crashes are due to observable distraction (Dingus et al., 2016), which indicates that driver distraction is a significant problem for road safety.

Driving while being distracted is defined as the diversion of attention away from activities critical for safe driving toward competing activities (Lee et al., 2008). A well-documented example of competing activities is the use of cellphones and particularly smartphones, which have been shown to significantly reduce driving performance (Horrey & Wickens, 2006; McKnight & McKnight, 1993; Strayer et al., 2006). Therefore, many countries have banned holding a smartphone while driving because of road safety concerns, but hand-free use is still permitted.

Over the past few years, in-vehicle infotainment systems (IVIS) like Android Auto and Apple CarPlay have become increasingly popular, a trend that is growing. Indeed, the IVIS market was valued in 2021 at 7.03 billion USD with a compound annual growth rate expected of 9.3% for the years 2022 to 2030 (Grand view research, s. d.). IVIS give drivers access to the same functionalities they have on their smartphones (navigation, communication, auditory entertainment and even watching videos) through a screen display thus eliminating the need for direct interaction with their smartphone. Many of these systems offer the advantage of optimizing the information processing of smartphone functionalities for drivers, making them safer for this purpose (Niedermaier et al., 2009). Nevertheless, IVIS still divert drivers' attention away from the road and visually, mentally and physically distract them (Lee et al., 2001; Strayer, Cooper, Goethe, et al., 2017; Strayer et al., 2011a). Because IVIS require multimodal and complex interaction to complete a task, visual, mental, and physical distraction can happen simultaneously, creating an impairment from one or more of these sources. A study that assessed the impact of two popular IVIS (Android Auto and Apple CarPlay) found that interacting with these devices physically and vocally increased the reaction time, an increase that was greater than driving under the influence of alcohol or cannabis (Ramnath et al., 2020). For these reasons, IVIS are a fruitful area for researchers and designers.

Nowadays, many cars are equipped with advanced driver assistance systems (ADAS) to help the driver prevent crashes and collisions and enhance road safety. They infer the distraction of the driver by assessing the vehicle's state and position by lateral deviation (e.g., lane departure) and longitudinal deviation (e.g., distance from the following and preceding cars). Examples of these systems are forward collision warning, lane departure warning or blind spot warning systems that send alerts to the driver but do not take preventive action. Other systems do take action like automatic emergency braking that autonomously applies the brakes to avoid or mitigate a collision with another car, pedestrian, or animal. ADAS may seem like a solution to prevent further human error from occurring when driving. However, the possibility that these systems may have unplanned consequences, even though they are designed to prevent them, has been raised (Amditis et al., 2005; Kiefer et al., 2005). One study found that drivers discount or ignore warnings even if they always accurately indicate a collision situation (Lee et al., 2002). The study did not present clear reason why people are ignoring the warnings, but the authors raise two possible explanations: (1) driver's lack of comprehension of the nature and purpose of the warnings; (2) driver's lack of trust in the warning system. In line with this study, Bliss and Acton found that a group that was using a forward collision warning system with 50% reliability had significantly fewer accidents with other cars than the groups with a system with 75% and 100% reliability (Bliss & Acton, 2003).

Moreover, ADAS react to the driver's mistakes or misjudgments and rely on the reaction of a distracted driver. In this case, they act more like a last resort solution than a real solution for preventing the occurrence of such events. Therefore, there is an important lapse between the moment the driver's attention is impaired and the moment the consequences of this impairment affect the vehicle's position. Studies have shown that crash probability increases linearly with the time spent off road by drivers (Green, 1999) and that glances greater than 2 seconds away from the road are correlated with increased crash/near-crash risk (Klauer et al., 2006) A 2-second time lapse may seem relatively short, but for road safety concerns it is critical because much can happen in such a short period of time. For example, at 100km/h a car can travel 55.6 meters in 2 seconds. This means that when driver attention comes back on-road the driving environment around him is not the same and thus his situation awareness will need to be updated. Furthermore, some studies suggest that a glance away from the road should not exceed 1.6 seconds instead of the 2 seconds recommended (Dingus et al., 2006; Horrey & Wickens, 2007; Liang et al., 2014).

Currently, researchers are trying to find solutions to reduce and eliminate distraction while driving by assessing IVIS functions and highlighting design considerations for manufacturers to integrate in their interface. Other researchers are developing better algorithms and alerts for ADAS to react and mitigate distracted drivers' mistakes (Sun et al., 2021) . However, little research has tackled inattention itself in order to prevent driver distraction. In this study, we explore how we can redirect a driver's visual attention on-road by using non-invasive, real-time physiological data to counter distractions caused by IVIS. To do so, we use eye tracking data to measure the driver's visual attention because it is likely to become an increasingly accessible and affordable technology for in-car security. Hence, the need to research it (Guasconi et al., 2017).

This study proposes and empirically evaluates a novel approach in the design of distracted driving countermeasures by detecting when the driver's off-road gaze exceeds a specified threshold, and by delivering both auditory and haptic alerts to redirect the driver's visual attention back onto the road. We expect that the use of the proposed countermeasure will lead to greater visual attention on the road during the interaction with the IVIS as well as better driving performance when using IVIS.

2 RELATED WORK

For communicating and notifying drivers, in-vehicle intelligent systems use different modalities, most commonly auditory and visual alerts in the form of sounds, lights, earcons and icons. Yet, with in-vehicle technologies like IVIS and ADAS we see a proliferation of alerts creating an excess of different signals that create confusion for drivers and reduce the effects of such alerts. Studies on driving distraction provide evidence that visual warnings slow the response time of drivers because of the high load this modality brings (Politis et al., 2014). Moreover, drivers under high perceptual load have a significantly lower awareness for auditory and visual stimuli than under low perceptual load. Additionally, the perceptual load seems to have had a greater negative effect on awareness of visual stimuli than auditory stimuli (Murphy & Greene, 2015). This results in the alert being missed when the visual and auditory demands of driving are too high, a phenomenon called inattentional blindness (Cartwright-Finch & Lavie, 2007). Hence, researchers have assessed new modalities for conveying alerts via new sensory channels, offering a promising way to convey information to drivers without causing more distraction or risking being missed (Dmitrenko et al., 2018; Ho et al., 2005b; Spence & Driver, 1997).

Because of its very successful employment in air and underwater navigation, tactile seems a promising modality for enhancing driver situation awareness (Chiasson et al., 2003; Rupert, 2000). Previous studies have shown the reliability of this modality to redirect driver visual attention in the context of reacting to a forward and rear-end collision warning and that drivers were reacting earlier with this modality than without it (Ho et al., 2005b, 2006; J. J. Young et al., 2003). Moreover, when using tactile modality, the detection and reaction time are not affected by concurrent visual demands, thus making this modality a great complement to driving (Sklar & Sarter, 1999). When comparing tactile modality to others, some research has shown that drivers perform similarly with haptic and auditory alerts (Lee et al., 2004b), and some has shown that tactile alerts perform better when compared to auditory and visual alerts (Baldwin & Lewis, 2014; Murata et al., 2017; Scott & Gray, 2008). These findings suggest that tactile modality can enhance the efficacy of alerts in a driving context.

More recently, Dmitrenko et al. (Dmitrenko et al., 2018) used scent to convey driving-related information. They found that an olfactive alert provides a more hedonic experience, and that it has the potential to improve driving behavior by providing hints one could miss when relying on visual stimuli only. Moreover, scents like rose or peppermint, with low arousal and/or positive valence, can reduce anger in drivers, leading to better driving behavior (Dmitrenko et al., 2020b).However, no studies have examined olfactive modalities for redirecting attention in a distracted driving context. Therefore, it is difficult to assess the effectiveness of this modality in a situation where reaction is an important factor.

Researchers have also combined multiple modalities to assess their effectiveness. In a non-driving related study, Forster et al. (Forster et al., 2002) concluded that reaction time is faster when modalities are presented together. In line with this study, Van Erp et al. (van Erp et al., 2015)suggested that bi-modal alerts are perceived to be more urgent than each of their uni-modal constituents. In a driving context, multiple studies have reached similar conclusions: Reaction time is smaller and perceived urgency higher for alerts for which modalities are presented conjointly (Ho et al., 2007; Politis et al., 2015). In addition, Biondi et al. (Biondi et al., 2017) found that a bi-modal alerts produce faster responses than their uni-modal counterpart in high-density traffic. They were also observed to be as effective in heavy traffic as in less dense situations. Overall, bi-modal alerts are more efficient for redirecting driver attention rapidly toward an imminent danger.

Because driving demands an important level of visual attention, visual alerts have a slower reaction time than auditory and tactile alerts in high urgency situations (Murata et al., 2013; Politis et al., 2014, 2015). Thus, bi-modal alerts that include a visual modality will be impaired. On the contrary, it has been shown that auditory-tactile bi-modality can promote faster reaction time to hazards (Murata et al., 2012, 2013). This study regroups the preceding findings to provide as a proposed countermeasure an alert that would redirect driver's visual attention onto the road with the lowest reaction time while being integrated with an IVIS. Other studies provide a comparison between multiple modalities to assess which one or which combination can promote a lower reaction time to hazardous events (Lee et al., 2004b; Politis et al., 2015; Scott & Gray, 2008). However, they are more about contributing to the body of knowledge rather than investigating new ways to implement those findings, which is what this study is intended to do.

3 METHOD

3.1 Participants

Study participants ranged in age between 21 and 46 (mean = 26.57 and SD = 5.51), with 8 identifying as males and 13 as females, for a total sample size of 21 participants. Each participant received a compensation of $30 for their participation. Participants were recruited via a research panel and were screened for being18 years old, having a valid driver's license in our jurisdiction (the simulator in this study uses the traffic code of this jurisdiction), wearing appropriate footwear, not being susceptible to motion sickness, epilepsy, skin allergies, or requiring glasses to drive. This study was approved by the Ethics Review Board of the researchers' institution (Certificate ID 3621).

3.2 Experimental design

For this study, we conducted a two-factor within-subject experiment in which the exposure to the countermeasure as well as the difficulty of the interaction was manipulated (low, medium, and high interaction difficulty). With on-road visual attention, driving performance, and subjective workload as the main dependent variables. There were three tasks:

(CM1) The first-time participants had to drive with the multimodal countermeasure on. (CM2) The second-time participants had to drive with the multimodal countermeasure on. (Control) Participants had to drive without the countermeasure. During the tasks, participants had to interact with the IVIS. There were three different types of interactions each with a different level of difficulty based on the visual demand required to complete them. In the low task difficulty condition, participants had to interact with a MESSAGING application in which the participants had to listen and sometimes respond to a message. The messages were to give driving indications that the participants had to follow and to ask questions to which participants had to provide a simple answer to make them vocally edit a message to send. This interaction was deemed of low difficulty because the application could be used by vocal command to dictate the message and/or manually for confirming a command. In the medium task difficulty condition, they had to interact with the NAVIGATION application where the participants had to enter a generic destination (e.g., Museum) using a verbal interaction and then select manually from a list a specific location (e.g., Museum of Fine Arts). This interaction was considered of medium difficulty because the participant had to search through a list, but all the specific locations were on the first page of the list, so they did not have to scroll down to find one. Finally, the third interaction (high task difficulty) was with a MUSIC application in which participants had to find a song and a playlist. There was a subscription for this application, so the participant had the option to select a particular song in the playlist with no advertising (e.g., In the playlist Top 80s, play the song “Call me” by Blondie). This interaction was considered high difficulty because people had to navigate the right playlist and then manually scroll down to find the song. There were 16 songs in each playlist.

3.3 Apparatus and instruments

The study took place in a usability laboratory equipped with a driving simulator. The simulator featured a driver’s seat (OMP Design 2), a pedal set, and a steering wheel (Thrustmaster T-GT II), all mounted on a t-slotted structure frame.

The simulation software that was used is City Car Driving enterprise edition (Forward Development, Novosibirsk, Russia) and was run on a PC computer with a 49-inch curved Samsung CHG90 QLED Gaming Monitor monitor (Samsung, Suwon, South Korea) and 2 Logitech X-240 speakers (Logitech, Lausanne, Switzerland) each located behind the screen. The two cameras that are part of the eye tracker Smart Eye Pro (Smart Eye AB, Gothenburg, Sweden) were situated in front of the screen, at the left and right bottom corners. Finally, for simulating the IVIS, a support was designed, and 3D printed so that it could hold a Samsung Galaxy Tab A8 SM-X200 tablet (Samsung, Suwon, South Korea) with the left edge of the screen at 12cm from the steering wheel and the bottom edge of the screen at 66.5 cm from the ground. The complete set-up is shown in Figure 1.

Apple CarPlay (Cupertino, United States) was the IVIS chosen in this experiment because it is a commonly used IVIS and for its ease of implementation. To emulate it on the tablet, a Carlinkit CPC200-Autokit dongle (Carlinkit, China) was used. For this purpose, an iPhone XR (Apple, Cupertino, United States) was connected via a cable to the tablet. For the experiment, we used the applications Apple Maps and Apple Messages that are natively on the iPhone, and we installed the Spotify application (Spotify AB, Stockholm, Sweden). Otherwise, there were no new applications on the phone except those available by default on the iPhone.

In order to track the fixation of the participants' visual attention during the experiment, we used Smart Eye Pro eye tracker. The two cameras that capture the data were placed at the left and right of the monitor, both in front of it. They were placed so they could cover most of the disparities between the participants' heights without compromising the quality of the data. Moreover, Smart Eye software allows modeling the 3D environment of the simulator, enabling us to capture the gaze on a curved screen, though most eye trackers work only with a 2D screen.

Figure 1. A picture of the driving simulator that was used in this experiment.

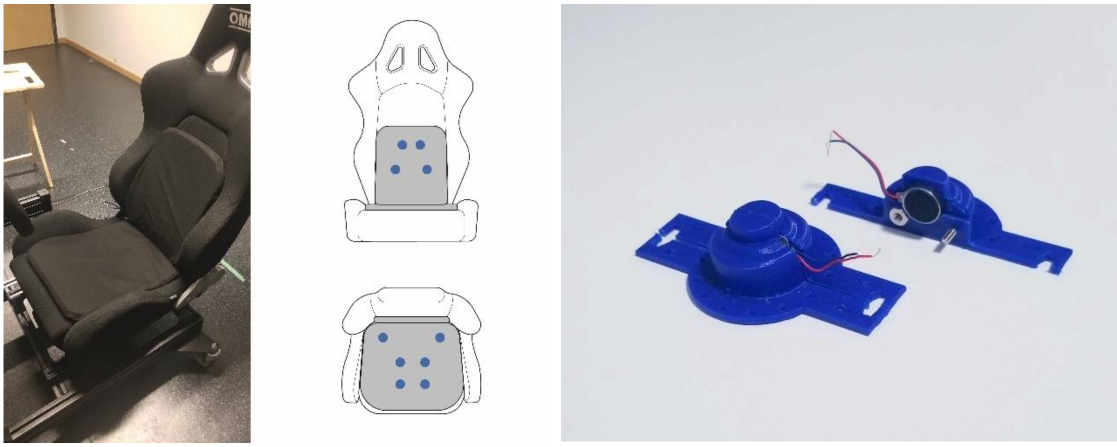
3.4 Countermeasure design

3.4.1Haptic and auditive alerts

A vibrotactile seat cushion was specifically designed by our team to send the haptic alerts to the driver. The cushion consisted of 10 mini vibrating motors (Adafruit – Vibrating mini disk motor) that were inserted in foam so that the participants would be more comfortable sitting on them. Six vibrating motors were positioned in the bottom cushion where the driver sits and four of them were positioned in the back cushion (see Figure 2.a). The vibration frequency used in this study is the effect #118 from the Arduino libraire (Adafruit_DRV2605 Library). Moreover, to protect and stabilize the tactile cushion when people are sitting on it, a textile cover was made. None of the participants noticed the presence of the cushion on the car seat during the study. Also, the cover was black to match the color of the driver's seat so that participants would not notice it. To protect the mini vibrating motors and stabilize the cable connection of the motors to the electrical circuit from wear, a shell was also designed (see Figure 2.b).

For emitting the auditive alerts, a simple speaker (Adafruit - Speaker - 3" Diameter - 4 Ohm 3 Watt) was used. The speaker was placed on the table in front of the curved monitor. The sound for this alert is the conventional red alarm used by Philips Intellivue Patient Monitoring for life threatening situations (Philips, Amsterdam, The Netherlands). It is a common high priority alarm use in the medical field. Finally, the vibrotactile seat cushion and the auditive alert speaker were both connected to the control unit.

The countermeasure alert consisted of one repetition of the vibration and sound that were triggered when the driver's gaze was located off-road (not directed at the screen) after a specific period of time. In the current study, we chose to set this threshold at 1.6 seconds building on a prior simulator study which suggested that 86% of observed collisions occur when the gaze exceeds this time (Horrey & Wickens, 2007). This is also in line with a study that uses data collected in the 100-Car Naturalistic Driving Study (Dingus et al., 2006), which examines the distribution of driver off-road glance duration. That study also found a similar result with off-road glance duration presenting a thicker tail when exceeding 1.7 seconds' duration (Liang et al., 2014).



(a) (b)

Figure 19. (a) A picture of the vibrotactile seat and a plan of the disposition of the mini vibrating motors on the seat cushion. (b) A picture of a closed shell with a mini vibrating motor inside (left) and the view inside the shell (right)

3.4.2Control unit

The mini vibrating motors and the speaker were controlled via an Adafruit HUZZAH32 microcontroller (ESP32 Feather Board) to which other components were connected. For the haptic alerts control, a motor driver (Adafruit – DRV2605L) was used to control all the haptic motors. For the auditive alerts, a soundboard (Adafruit Audio FX Mini Sound Board) was used to upload the alert sound and play it as well as a stereo amplifier (Adafruit - Adafruit TPA2016 2.8W) to control the speaker. In order to power this system, the microcontroller was connected via cable to the computer that was running the eye tracker software with a power of 3.2V. The reason why the system was connected to this computer specifically is that we use the live data from Smart eye to set off the countermeasure. More precisely, when Smart eye detects that the driver’s gaze is farther off the screen than the established threshold, it triggers the tactile and auditory alerts. This was made possible by a C++ code developed by the research team.

3.5 Protocol

Participants were greeted and had to complete a consent form; then they were installed in the driving simulator and the eye tracker was calibrated. If needed, the seat was adjusted so that the participants were in a driving position in which they felt comfortable. Finally, participants were asked to fill in a first questionnaire about their driving experience.

Before starting the driving tasks, participants had to carry out a familiarization task for 15 minutes with CarPlay and the simulator. While they were seated, they were first taught how to use the interface of CarPlay and the three applications employed in the experiment. Consequently, all the participants used the system in the same way and those who had never interacted with CarPlay could familiarize themselves with it. Next, they were taught how to start and control the car before the experiment began. The objective of this first drive was to give them some experience with the environment and the simulation. During this drive, they also had to accomplish one interaction with each of the 3 applications (i.e., Messaging, Navigation and Music) to validate their abilities to use them correctly.

Before each task, participants were asked to keep the speed between 50-60 km no matter the speed limitations they saw. Also, they were asked to follow the traffic code of the jurisdiction where this study took place. Finally, they were told to drive and act in a natural way.

The three tasks of this study (CM1, CM2, control) were each organized with the same sequence of interactions: *messaging, navigation, messaging, messaging, music, messaging, messaging, music, messaging*. The messages before the navigation and the music interactions contained instructions for participants regarding these interactions. The messages after those interactions contained simple questions (e.g., Have you found the right song?). Moreover, the tasks were randomized in three different sequences: (1) CM1→CM2→control (2) CM1→control→CM2 (3) Control→CM1→CM2.

3.6 Measures

To assess the effectiveness of the countermeasure in fulfilling the role of keeping the visual attention of the driver on the road, we looked at the resulting distribution of the driver fixation on-road and off-road; specifically, we measured the OFF-ROAD FIXATION RATE as well as the OFF-ROAD FIXATION TIME. The OFF-ROAD FIXATION RATE is computed by dividing the time when driver's gaze was off-road (off-road fixation time) by the time required to complete the non-driving related tasks (fixation time off-road + fixation time on-road). Thus, this reflects the extent to which the driver redirects his/her attention back to the road for shorter periods during his interaction with the IVIS. OFF-ROAD FIXATION TIME is the time in seconds when the participant had fixated his gaze outside of the main screen of the simulator during the interaction with the IVIS.

The NASA-TLX was also used for assessing the mental workload of the driver following his experience with the IVIS and the countermeasure. The NASA-TLX includes 6 subscales that measure the perceived a) Mental Demand, b) Physical Demand, c) Temporal Demand, d) Performance, e) Effort, and f) Frustration of the experienced task on a scale from 0 to 100 (Hart & Staveland, 1988). This measure is used to investigate the workload of using the IVIS while driving and how it changes with the presence of the proposed countermeasure.

The NUMBER OF ROAD VIOLATIONS was measured to evaluate the impacts on road safety, since drivers are more susceptible to missing roadway indications and having poor driving performance when they are distracted (Donmez et al., 2006; Horberry et al., 2006; Oviedo-Trespalacios et al., 2016). This measurement was gathered by the simulator (City Car Driving Enterprise), which saves all the road violations made by the participants, including lane departure, failing to maintain a safe distance between vehicles, no respect of the priorities, and collision with another solid body (vehicle, pedestrian, etc.).

Finally, we measured the NUMBER OF TRIGGERED ALERTS to quantify the adaptation behavior of drivers to the implemented countermeasure and compare both conditions in which they experienced this countermeasure.

3.7 Analysis

Analyses to assess between-conditions differences were performed for each dependent variable using RM ANOVA, with the participants' perceived CarPlay experience as a covariate. The "time of fixation off-road" is the only dependent variable for which there was a significant two-way interaction; the results present the significant between-conditions differences for each interaction type. The significant threshold for all tests was set at $p \leq 0.05$, with a confidence level of 0.95. All analyses were conducted using "afex" and "emmeans" libraries of the R software (R core team, 2022).

4 RESULTS

4.1 Off-road Fixation Rate

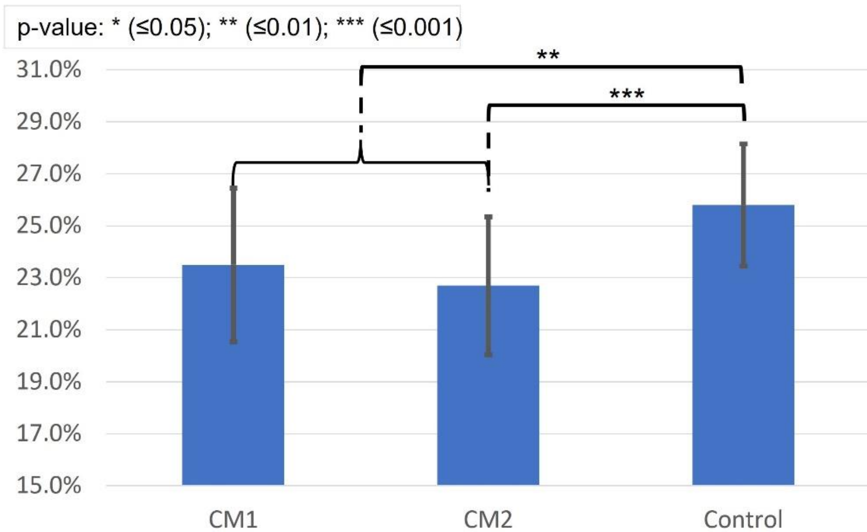


Figure 20 Off-Road Fixation Rate

There are significant differences in the off-road fixation rate between 1) both factors with the countermeasure and the control condition, as well as 2) between the condition in which the participants experienced the countermeasure for a second time and the control condition. The estimated difference between the control condition and the conditions with the countermeasure was 2.70%, with a 95% confidence interval of [1.26%; 4.13%] and a p-value of 0.002. The estimated difference between the condition of the second use of the countermeasure and the control condition was 3.11% with a 95% confidence interval of [0.01625; 0.046] and a p-value 0.001. This result shows that a greater proportion of time was spent off-road when participants were not exposed to a countermeasure and this difference is higher when we consider only the second time they were exposed to the countermeasure.

4.2 Off-road Fixation Time

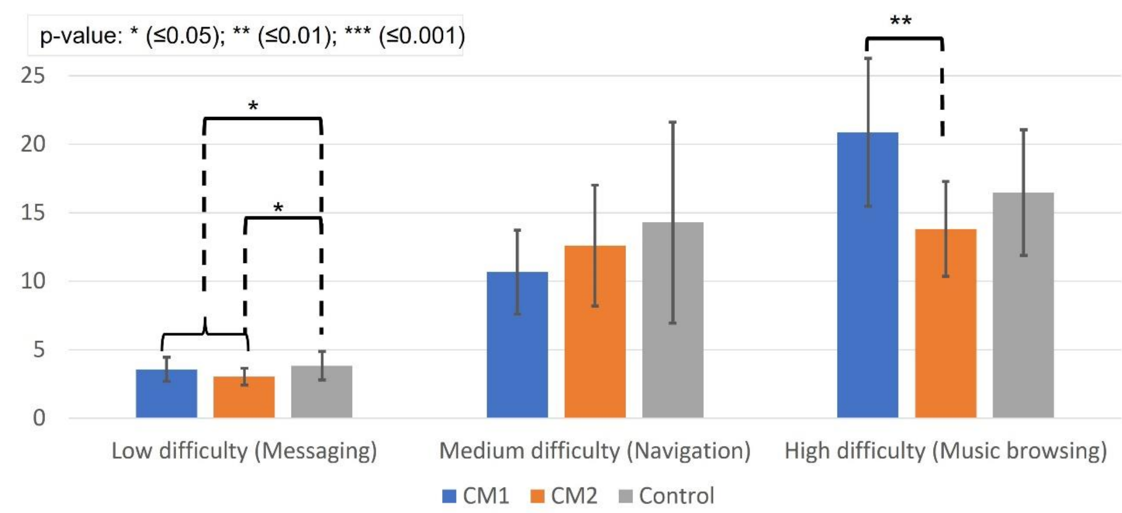


Figure 21 Off-Road Fixation Time (seconds)

The RM ANOVA on the off-road fixation time showed a significant interaction between the exposure to countermeasure factor and the level of difficulty of interaction that the participants were engaged in.

Regarding the low difficulty factor (i.e., messaging interaction), the contrast analysis shows a significant difference between both conditions with the countermeasure and the control condition, as well as a significant difference between the condition where participants experienced the countermeasure for a second time and the control condition. The estimated difference between the conditions with the countermeasure and the control condition was 0.54s with a 95% confidence interval of [0.08s; 0.99s] and a p-value of 0.028. The difference between the condition of the second exposure and the control condition was 0.81s. with a 95% confidence interval of [0.015s; 1.46s] and a p-value of 0.023. This result shows that for the low difficulty task, participants spend more fixation-time off-road when they were not exposed to the countermeasure, and this difference increases when compared to the second exposure to the countermeasure.

In the music browsing interaction, there was a significant difference between the first time and the second time participants experienced the countermeasure. The estimated difference was 7.06s. with a 95% confidence interval of [2.14; 11.98] and a p-value of 0.012. This result indicates that for the high difficulty task, participants spend less fixation-time off-road when they were exposed to the countermeasure the second time in comparison to the first time they were exposed to the countermeasure.

4.3 Number of road violations

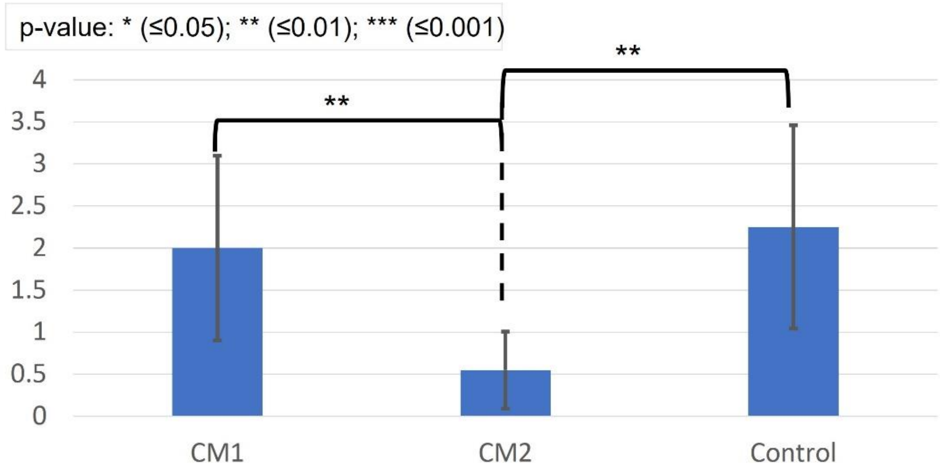


Figure 22 Number of Road Violations

For the number of road violations made by participants, there were significant differences between 1) the condition in which participants experienced the countermeasure for a second time and the control condition, and 2) the condition in which participants experienced the countermeasure for the first time and that in which participants experienced the countermeasure for the second time. The estimated difference between the control condition and the condition of the second use of the countermeasure was 1.70, with a 95% confidence interval of [0.70; 2.70] and p-value of 0.004. The estimated difference between the condition of the first use of the countermeasure and the condition of the second use of the countermeasure was 1.45 with a 95% confidence interval of [0.46; 2.44] and p-value of 0.010. These results show that participants had made less road violations when they were exposed to the countermeasure for the second time in comparison to when they were not exposed to a countermeasure as well as to when they were to the countermeasure for the first time.

4.4 Nasa_Tlx

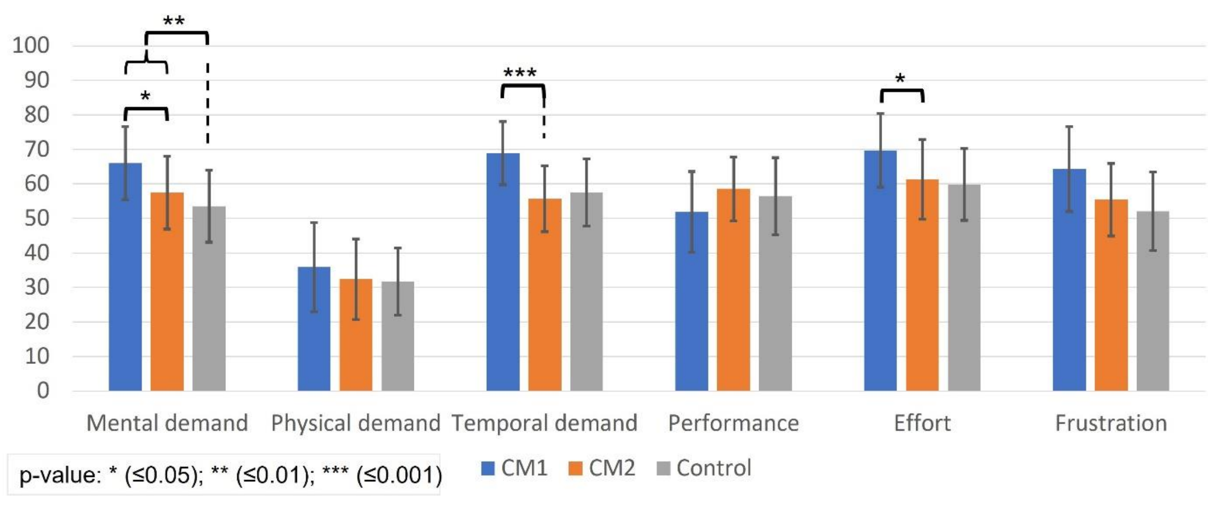


Figure 23. NASA-TLX

The RM ANOVA analyses on the NASA-tlx measures reveal that there are significant differences between conditions in terms of mental demand, temporal demand, and effort, but that there are none in terms of physical demand, performance, and frustration.

For mental demand, there were significant differences between 1) both conditions with the countermeasure and the control condition, as well as 2) the condition in which participants experienced the countermeasure for the first time and that in which participants experienced the countermeasure for the second time. The estimated difference between the control condition and the conditions with the countermeasure was -8.19, with a 95% confidence interval of [-13.36; -3.02] and a p-value of 0.007. The difference between the condition of the first exposure and the second exposure to the countermeasure was 8.57, with a 95% confidence interval of [1.75; 15.4] and a p-value of 0.021. These results show that participants experience lower mental demand when they are not exposed to the countermeasure. However, this difference in mental demand is nonsignificant when they were exposed to a countermeasure the second time.

For temporal demand, there was a significant difference between the condition in which participants experienced the countermeasure for the first time and in which participants experienced the countermeasure for the second time. The difference between the first and second exposures to the countermeasure was 13.19, with a 95% confidence interval of [7.47; 18.91] and a p-value of ≤ 0.001. This result indicates that participants experience lower Temporal demand when they are exposed to the countermeasure the second time in comparison the first exposure to the countermeasure.

Similarly, for effort, there was a significant difference between the condition in which participants experienced the countermeasure for the first time and that in which participants experienced the countermeasure for the second time. The difference between the first and second exposures to the countermeasure was 8.43, with a 95% confidence interval of [1.97; 14.88] and a p-value of 0.018. This result indicates that participants experience lower Effort when they are exposed to the countermeasure the second time in comparison the first exposure to the countermeasure.

4.5 Number of triggered alerts

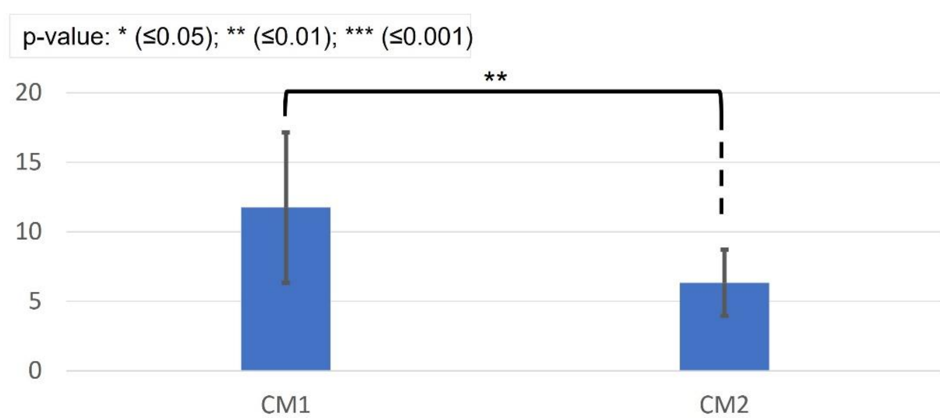


Figure 24 Number of Triggered Alerts

For the number of triggered alerts, there was a significant difference difference between the condition in which participants experienced the countermeasure for the first time and that in which participants experienced the countermeasure for the second time. This difference was estimated at 5.4 activations with a 95% confidence interval of [1.89; 8.91] and a p-value of 0.008. This indicates that participants trigger the countermeasure's alert less when they are exposed to the countermeasure the second time in comparison the first exposure to the countermeasure.

5 DISCUSSION

The results of the present study show that the negative effect of driver distraction on driving performance is reduced by the presence of the proposed countermeasure. When looking at the off-road fixation time, we find that the only statistically significant difference between the control and the countermeasure conditions is related to the low difficulty factor, i.e., messaging interaction, in which the time spent off road decreases by an estimated .5s in the presence of the countermeasures and by .8s if we consider only the second exposure to the countermeasure. In contrast, the differences regarding the two other levels of difficulty, i.e., navigation and music browsing, were non-significant. This can be explained by the nature of the interactions. While most of the information necessary for messaging is communicated by the vocal assistant Siri, this is not the case for music browsing and navigation interactions where drivers must read information available on the IVIS screen to complete their tasks.

As for the off-road fixation rate, it is reduced regardless of the interaction type. While the reduction of the off-road fixation rate can be attributed to the reduction of the off-road fixation time for the messaging interaction, this is not the case for the navigation and music browsing interactions. The reduced off-road fixation rate in these two interactions with the non-significant difference in the off-road fixation time indicates that the drivers increased their time fixation on the road during the beginning and end of their interactions with the IVIS screen in the countermeasures conditions. In other words, during their interaction with the IVIS screen to look for specific music or to find a specific address, they redirected their gaze to the road for longer periods in the presence of the countermeasure in comparison to absence of countermeasures.

This indicates two different behavioral patterns that emerged when the participants interacted with the IVIS screen in the presence of the countermeasure. The first is specific to the interaction in which most of the information is delivered vocally and the stimuli presented on the screen do not offer additional critical information for the interaction. In this case, the drivers reduced the time spent directing their gaze on the IVIS screen and directed it instead onto the road. The second type of interaction involves most of the information being presented visually on the screen. In this case, while the total time the drivers spent directing their gaze on the screen does not change much, the drivers spend more time looking at the road in between the intervals spent looking at the IVIS screen.

The effectiveness of the countermeasure goes beyond the redirecting of the visual attention onto the road and translates into the performance of the drivers as reflected in the number of traffic violations committed. This difference in the number of violations was especially significant the second time participants experienced the proposed countermeasure. This points towards a relatively fast learning effect as the participants adapted to the alerts associated with countermeasures and thus changed their behavioral patterns accordingly. This is in line with (Dingus et al., 2006; Horrey & Wickens, 2007; Liang et al., 2014), as our results showed fewer road violations when the driver had their gaze redirected after a 1.6 second threshold and when they were more familiar with the countermeasure. Thus, instating evidence for the validity of this threshold for road safety application.

This learning effect is accompanied by a significant drop in the subjective workload between the first and second times participants experienced the countermeasure measured by the NASA-TLX in the subscales of Mental Demand, Temporal Demand and Effort. While there are differences in the Mental Demand, Temporal Demand and Effort when comparing the first experience of the countermeasure and the control condition, these differences are non-significant when comparing the second time participants experienced the countermeasure and the control condition. This finding shows that while drivers might experience an increased workload with the first use of such the countermeasure, this increase subsequently disappears and the level of workload becomes similar to that of the absence of the countermeasure.

An interesting behavioral adaptation when comparing the first and second condition in which participants experienced the countermeasures, is reflected in the lower number of alerts that were triggered the second time. Instead of redirecting their gaze to the road after the alert was triggered, participants became familiar with the time it takes to trigger the alert and were trying not to do so by redirecting their attention to the road before the alert was triggered. This shows a change of behavior not directly related to the alert of the countermeasure but merely to the presence of countermeasure itself.

Actual studies on the integration of eye tracking are about real-time assessment of the driver state and to which reliability they can assess it (T. Hecht et al., 2019b). The present study goes a step further in the implementation of eye tracking technology in-vehicle by providing an example of real-time data application in a driving context.

The proposed system enhances road safety and limits the impact of distractions. As such, policy makers can introduce new regulations for car manufacturers around the implementation of similar systems in new vehicles to mitigate the increasing IVIS distraction. While actual distraction mitigation systems are about reducing the distraction potential of IVIS and reacting to distracted driver's mistakes with ADAS, similar countermeasures that prevent distractions could be considered as an additional and potentially more efficient layer to be integrated to in-vehicle technologies to mitigate driver distraction.

Future research could further investigate drivers' trust in and annoyance with this countermeasure, as it is linked to the adoption or dismissal of it (Bliss & Acton, 2003; Kiefer et al., 1999), if it is the choice of the driver. Furthermore, the learning effect and the different behavioral adaptations of drivers using the countermeasure presented could be re-examined to determine the extent of their influence. Further research is also needed to test the effectiveness of the countermeasure in a more ecologically valid environment.

6 CONCLUSION

This study advances a new countermeasure to reduce drivers' distraction while driving and find support for its use. Indeed, the use of an auditive and haptic alert when drivers' gaze off-road exceeds 1.6 seconds leads to more time spent visually on-road as well as fewer road violations when drivers are interacting with an IVIS. This suggests that a countermeasure reacting directly to a driver's inattention instead of reacting to a driver's mistakes resulting from inattentioncan be a way to enhance road safety.

Furthermore, the countermeasure seems to have a learning effect on participants when they attempt to avoid triggering the alerts. It appears that their behavior was more about trying to prevent the alert rather than reacting to it.

This study also contributes by showing the potential application of eye tracking technologies in vehicles that assess driver's visual attention in real time, hence allowing the countermeasure to prevent the effects of distraction before they occur.

The study's results advocate using eye tracking technologies to help reduce drivers' distraction as a potentially useful and effective addition to in-vehicle technologies, thus necessitating further investigation by researchers and car manufacturers.