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HEC MONTRÉAL

Améliorer le réalisme en simulation de course: Les effets médiateurs des états psychologiques optimaux sur la performance grâce à la technologie haptique

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Résumé

Cette étude examine la médiation des états psychologiques optimaux, particulièrement l'état de *flow* et l'état décisif, sur les performances en simulation de course, et leur relation avec le retour de force haptique. L'état de *flow*, défini comme un état d'immersion totale avec une concentration accrue, et l'état décisif, caractérisé par une performance maximale sous pression, sont des concepts clés pour comprendre les performances sportives optimales. Si l'utilisation du retour haptique contribue au niveau d'immersion, la compréhension de ces états psychologiques optimaux permet aux conducteurs d'exploiter pleinement la technologie à leur disposition. Cette recherche se concentre sur la façon dont l'état de *flow* et l'état décisif médient la relation entre la fidélité haptique et les performances dans les environnements de course virtuels. Un échantillon de 25 experts de simulation de course a participé à des courses en utilisant cinq simulateurs de voiture au niveau de fidélité haptique varié. L'étude a révélé que les états de *flow* et décisif médient de manière significative l'effet de la fidélité haptique sur les performances et l'espérance de succès. Cette recherche offre de nouvelles perspectives sur l'état décisif, un concept jusqu'à maintenant seulement présent dans les sports traditionnels, et les mécanismes de performance en simulation de course, par le biais d'une analyse quantitative. Ces résultats sont particulièrement utiles pour les concepteurs et les développeurs, car ils guident l'optimisation des systèmes haptiques afin d'améliorer l'interaction avec l'utilisateur et les performances dans un contexte virtuel.

Mots clés : États psychologiques optimaux, performance, sports électroniques, haptique, expérience optimale, état décisif, environnement virtuel, simulation

Méthodes de recherche : Expérimentation, recherche quantitative, environnement virtuel, mesures autodéclarées par questionnaire, test statistique

Abstract

This study investigates the role of optimal psychological states, particularly flow and clutch states on performance outcome in racing simulation and their relationship with haptic feedback. Flow state, defined as a total immersion state with heightened concentration, and clutch state, characterized by peak performance under pressure, are key concepts for understanding superior sporting performance. While the use of haptic feedback contributes to the level of immersion, understanding these optimal psychological states enables drivers to fully exploit the technology at their disposal. This research focuses on what extent the flow and clutch states mediate the relationship between haptic fidelity and performance outcomes in virtual racing environments. A sample of 25 racing simulation experts participated, completing races using five different car simulators with varying levels of haptic fidelity. The study revealed that flow and clutch states significantly mediate the effect of haptic fidelity on performance and expectancy of success. The research offers new insights into the clutch state, a concept until now only present in traditional sports literature, and performance mechanisms in racing simulation, through quantitative analysis. These results are particularly beneficial for designers and developers, guiding the optimization of haptic systems to improve user interaction and performance in virtual contexts.

Keywords : Optimal psychological states, Performance, eSports, Haptic, Flow, Clutch, Virtual environment, Simulation

Research methods : Experimentation, quantitative research, virtual environment, self-reported measures by questionnaire, statistical test

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Liste des abréviations

PSD: Power spectrum density

HRI: Haptic Response Index

FSSS: Flow State Short Scale

CSS: Clutch State Scale

UTC: Coordinated Universal Time

Avant-propos

Ce mémoire en expérience utilisateur a été soumis avec l'autorisation de la direction administrative du programme de la Maîtrise ès Science en Gestion de HEC Montréal.

Le projet de recherche lié à ce mémoire a obtenu l'approbation du comité d'éthique en recherche (CER) de HEC Montréal le 29 mars 2023 sous le numéro de projet 2023-5396. Un article issu du projet est inclus dans ce mémoire avec le consentement des coauteurs.

L'article est actuellement en préparation pour soumission au journal *International Journal of Human-Computer Interaction.* Il explore la relation entre la technologie haptique, les états psychologiques optimaux et la performance.

Remerciements

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Chapitre 1: Introduction

1.1 Mise en contexte de l'étude

L'usage de la simulation est largement répandu dans le domaine sportif à des fins d'entraînement (Cecil et al., 2021; Checa and Bustillo, 2020; Sadeghi Milani et al., 2024; Walch et al., 2017; Zahabi and Abdul Razak, 2020) et les simulateurs sont considérées comme des outils de formation éprouvés (Fleming and Sturm, 2014). Les simulateurs offrent un environnement sûr et contrôlé pour développer des compétences sans les risques associés à un environnement réel (de Winter et al., 2012) et ont évolué vers des plateformes technologiquement avancées qui simulent les dynamiques du monde réel (Scacchi, 2018). En course automobile, par exemple, les équipes professionnelles les emploient pour la formation des pilotes, la formulation de stratégies de conduite et l'analyse de performance des pilotes (Bugeja et al., 2017; de Winter et al., 2012; Knox, 2011; Sturm, 2019; Tudor, 2020).

Au-delà de l'aspect technique, la performance sportive est intrinsèquement liée aux états psychologiques des athlètes (Nagorsky and Wiemeyer, 2020). Il est important de considérer les états mentaux dans le domaine du sport puisqu'ils jouent un rôle crucial dans la performance, la motivation intrinsèque et le bien-être des athlètes (Swann et al., 2022). Ces états psychologiques sont indispensables à la compréhension des performances sportives.

En particulier, l'état de *flow*, un concept déjà bien ancré dans la littérature scientifique du sport, a été largement étudié pour son lien avec la performance (Csikszentmihalyi, 1975; Harris et al., 2021; Jackman et al., 2021; Swann et al., 2017a). Le *flow* est caractérisé par un état d'immersion profonde et de concentration accrue où les individus ressentent une synergie entre leurs compétences et la tâche à accomplir, souvent accompagnée d'une perte de la notion du temps (Nakamura and Csikszentmihalyi, 2002). Cet état peut aider à comprendre les expériences d'une personne absorbée dans une situation sportive (Csikszentmihalyi, 1990). Les interventions permettant d'induire les expériences de *flow* sont très valorisées par les athlètes, les entraîneurs et les praticiens (Swann et al., 2018) puisqu'il est associé avec des performances optimales, ainsi qu'un sentiment d'accomplissement et de bien-être (Boudreau et al., 2020; Harris et al., 2021).

Des recherches récentes révèlent que la performance optimale ne peut être entièrement expliquée uniquement par le *flow* (Harris et al., 2021). En effet, un deuxième état mental, distinct de l'état de *flow,* serait sous-jacent à des performances optimales; l'état décisif (traduction du terme anglais *clutch*) (Swann et al., 2016). Nonobstant son apparition récente dans la littérature, l'état décisif suscite un intérêt croissant des chercheurs (Schweickle et al., 2021). Cet état mental se manifeste par des performances maximales dans des situations de haute pression, typiquement lors des moments cruciaux d'une compétition (Swann et al., 2017a). En outre, la capacité à réussir sous pression ne contribue pas seulement à une expérience plus gratifiante et agréable pour les athlètes (Otten, 2007), mais est également considérée comme un facteur déterminant de réussite dans le sport (Mesagno and Mullane-Grant, 2010; Swann et al., 2019, 2016). Les performances dans ces moments sous pression sont souvent décisifs sur l'issue d'une compétition (Hibbs, 2010).

Dans la littérature scientifique francophone, l'état de *flow* est souvent traduit comme une expérience optimale. Cependant, les recherches récentes, en intégrant l'état décisif dans l'analyse de la performance, montrent que l'expérience optimale se répartit en réalité entre ces deux états (Boudreau et al., 2022; Harris et al., 2021; Houge Mackenzie et al., 2023; Schweickle et al., 2021). Par conséquent, qualifier exclusivement l'état de *flow* d'expérience optimale pourrait prêter à confusion. C'est pour cette raison que nous avons décidé de maintenir le terme original dans ce texte. Ce choix est également motivé par la notoriété du concept dans le domaine de la recherche, où sa signification est largement reconnue par la communauté scientifique. Il est à noter que la plupart des publications francophones traitant de l'état de *flow* conservent aussi ce terme original (Demontrond and Gaudreau, 2008; Heutte, 2017).

Bien que l'état de *flow* et l'état décisif partagent certaines dimensions, telles que l'exécution automatique des compétences, des perceptions altérées, une absorption profonde et une confiance accentuée (Swann et al., 2017c), ces deux états surviennent indépendamment l'un de l'autre (Swann et al., 2017a), et potentiellement à différents moments lors d'une même activité. Alors que l'état de *flow* est caractérisé par une expérience sans effort, l'état décisif se distingue par un effort maximal et une concentration intense (Swann et al., 2017a). De plus, dans un état décisif, l'individu est souvent très conscient de l'importance de sa performance et des enjeux, contrairement à l'état de *flow*, ou cette conscience peut être diminuée en raison de l'immersion dans l'activité (Swann et al., 2017a).

En raison de leur nature distincte, mais complémentaire, la compréhension de l'état décisif, en plus de l'état de *flow,* est susceptible d'offrir une perspective plus complète sur les mécanismes psychologiques qui influencent les performances de haut niveau (Swann et al., 2022), en particulier dans des contextes de forte pression et d'enjeux élevés.

Dans ce contexte, les sports électroniques offrent un terrain d'étude idéal pour explorer ces états psychologiques optimaux. Définis comme un type de sport où les actions permettant son développement sont facilitées par des systèmes électroniques (Hamari and Sjöblom, 2017), les sports électroniques reflètent les mêmes exigences de performance que les sports traditionnels, tout en offrant de nouvelles avenues de recherche sur l'interaction entre les composantes physiques et numériques (Pluss et al., 2019).

Les sports électroniques, bien plus qu'un simple divertissement, ont évolué pour devenir un phénomène mondial dont le nombre d'adeptes ne cesse de croître. De 2015 à 2022, plutôt que d'être de modestes événements de jeu, les sports électroniques ont connu une croissance exponentielle (Sjöblom et al., 2019; Zhang and Liu, 2022) et sont devenus une industrie importante, avec une évaluation de 24,9 milliards de dollars américains en 2019 (Ahn et al., 2020). Cette industrie a d'ailleurs généré 1,384 milliard de dollars en 2022 pour les éditeurs de jeux, les organisateurs d'événements, les joueurs et les équipes (Statista, 2023). Son audience s'étend sur des centaines de millions de personnes; 532 millions de téléspectateurs ont assisté à des compétitions de sports électroniques en 2022 (Newzoo, 2022).

La simulation virtuelle de course automobile a également suivi ce gain de popularité pour les sports électroniques. Durant la pandémie de la Covid-19, la F1 et la Nascar se sont tournées vers des diffusions en direct de courses simulées, impliquant à la fois des pilotes professionnels et des pilotes de simulation de course (Scacchi, 2021a), ce qui a renforcé l'attrait pour cette forme de divertissement. L'audience des simulations de course est ainsi passée de 2,2 millions en août 2020 à 4,4 millions en janvier 2021 (Hatchet, 2021).

La simulation de course reproduit fidèlement les aspects complexes des courses réelles (Paiva, 2015; Tudor, 2020), ce qui enrichit son aspect de divertissement, mais en fait aussi un outil de formation grandement apprécié. En combinant l'enthousiasme des sports traditionnels avec une technologie de simulation avancée, la simulation de course offre une expérience numérique à la fois authentique et accessible des courses automobiles (Crawford et al., 2019; Sturm, 2019). Cette facette des sports électroniques ne se contente pas de capturer l'essence des sports traditionnels, mais introduit également de nouvelles dimensions grâce à sa plateforme virtuelle.

La simulation joue un rôle clé dans l'entraînement des sports électroniques. En particulier, la technologie haptique, lorsque implantée adéquatement, permet d'enrichir cette expérience de simulation (Cummings and Bailenson, 2016). En intégrant le retour d'information tactile dans les équipements tels que les volants, les pédales et le siège, la technologie haptique avec un haut niveau de fidélité offre une expérience plus authentique et immersive (Bugeja et al., 2017; Young and Lenn, 2017). Cette immersion améliorée est cruciale, non seulement pour l'expérience de jeu, mais aussi pour la performance des joueurs. En simulant les sensations physiques du monde réel, la technologie haptique permet aux joueurs de développer une compréhension plus intuitive des réactions du véhicule et des conditions de course (Calleo et al., 2023; Klarica, 2001), des éléments essentiels à la performance dans les compétitions virtuelles et réelles. C'est précisément cet relation entre la technologie et la performance qui se révèle déterminante dans le domaine compétitif des sports électroniques (Nagorsky and Wiemeyer, 2020).

L'aspect de la performance dans les sports électroniques, en particulier dans la simulation de course, est essentiel pour comprendre les progrès des athlètes (Pedraza-Ramirez et al., 2020), comme dans n'importe quel autre domaine sportif. Les facteurs déterminant la performance dans ces environnements virtuels sont complexes et multidimensionnels, englobant à la fois des aspects technologiques, tels que la fidélité de la simulation et la qualité de l'expérience haptique (Calleo et al., 2023; Sigrist et al., 2013), et des facteurs psychologiques, comme les états mentaux et émotionnels des joueurs (Nagorsky and Wiemeyer, 2020; Swann et al., 2019; Voss et al., 2010). Comprendre de quelle manière l'environnement d'un individu influence son état mental est crucial pour optimiser la performance et l'expérience des athlètes.

1.2 Énoncé du problème

L'intégration de la technologie haptique dans un contexte de simulation de course a ouvert de nouvelles voies pour explorer son impact sur la fidélité de la simulation, et ses effets ultérieurs sur les performances des joueurs. Le problème central qui nous intéresse ici est de comprendre comment le niveau de fidélité, amélioré par le retour haptique, influence l'atteinte des états psychologiques optimaux de *flow* et décisif et comment ces états peuvent affecter les résultats des performances dans un contexte de simulation de course. Une meilleure compréhension de l'influence de la technologie haptique sur les états mentaux sous-jacents à une performance optimale est importante dans le but de concevoir de meilleurs systèmes.

La technologie haptique, en fournissant un retour d'information tactile qui imite étroitement les expériences du monde réel, augmente la perception de réalisme pour l'utilisateur (Muender et al., 2022). On suppose que ce réalisme accru peut favoriser une immersion plus profonde des joueurs (Scacchi, 2021a; Sreelakshmi and Subash, 2017), ce qui pourrait permettre d'entrer plus facilement dans un état de *flow* (Chen and Lin, 2022). Dans un tel état, les joueurs ressentent un sentiment de contrôle et d'attention accru (Swann et al., 2017a), ce qui est primordial pour relever les défis complexes de la course automobile. Une simulation plus réaliste, améliorée par un retour haptique, induit-elle de manière plus fiable un état de *flow* chez les joueurs, et cela conduit-il, à son tour, à de meilleurs résultats en termes de performances?

De même, le problème s'étend à la compréhension du rôle de la fidélité de la simulation sur l'état décisif. Dans les scénarios à haute pression, où la précision et la prise de décision en une fraction de seconde sont essentielles (Hibbs, 2010; Swann et al., 2019), le retour d'information fourni par la technologie haptique pourrait influencer les individus à adopter un comportement réaliste (Mullen et al., 2011). Dans un contexte hautement compétitif comme les sports électroniques (Jang and Byon, 2019), il fait du sens de s'intéresser aux performances optimales réalisées sous pression. Nous cherchons donc à déterminer si une simulation à haute fidélité contribue à la capacité d'un pilote à entrer plus efficacement dans un état décisif et comment cela impacte les performances de course.

Par conséquent, le problème central de cette recherche tourne autour de l'influence de la technologie haptique et du niveau de fidélité de la simulation sur la capacité à entrer dans les états de *flow* et décisif et leur impact collectif sur les résultats des performances en simulation de course. Cette recherche vise à donner un aperçu de la manière dont les améliorations technologiques apportées aux simulations de jeu peuvent aller au-delà du simple réalisme physique et influencer les aspects psychologiques du jeu, ce qui se répercute en fin de compte sur les performances et l'expérience du joueur.

1.3 Objectifs de recherche et contributions potentielles

L'objectif de ce mémoire est de mieux comprendre les mécanismes psychologiques sous-jacents à la performance dans un contexte de sport électronique en étudiant les impacts de la technologie haptique sur le niveau de réalisme dans un environnement virtuel et ainsi évaluer l'impact qui en résulte sur la performance de l'utilisateur dans une situation de simulation de course. Ce mémoire met donc l'emphase sur l'utilisation de la technologie haptique dans un simulateur de course automobile, et l'expérience des utilisateurs avec ces systèmes.

D'un point de vue théorique, cette recherche promet d'étendre la compréhension de l'état décisif vers des contextes de performance numérique. Ce concept, qui fait son apparition dans la littérature scientifique récemment (Swann et al., 2017a), attire l'attention des chercheurs pour son lien avec des performances intrinsèquement gratifiantes et motivantes (Swann et al., 2017b). Ainsi, faciliter l'apparition de cet état est d'un grand intérêt pour les chercheurs et les praticiens dans le domaine de la psychologie du sport (Schweickle et al., 2023, 2021). En examinant comment l'état de *flow* et l'état décisif influencent la performance dans les environnements virtuels, cette étude pourrait apporter des réflexions intéressantes sur la psychologie cognitive et la psychologie du sport, en particulier en ce qui concerne l'humain et la technologie.

D'un point de vue pratique, cette recherche pourrait contribuer à améliorer les méthodes d'entraînement dans les sports électroniques. En mettant en évidence l'efficacité de la technologie haptique pour augmenter le réalisme des simulations et améliorer la performance, elle pourrait conduire à des stratégies d'entraînement plus immersives et efficaces pour les athlètes de sports électroniques. De plus, bien que centrée sur les sports électroniques, les implications de cette étude pourraient s'étendre à l'entraînement des pilotes de course réels, fournissant des insights précieux sur l'utilisation des simulations virtuelles pour améliorer les compétences de conduite.

Cette étude pourrait aussi permettre aux concepteurs de systèmes haptiques et d'environnements virtuels de développer de meilleurs systèmes, en ayant une meilleure connaissance de l'expérience de l'utilisateur.

Ce mémoire répond donc à une question de recherche suivante:

Dans quelle mesure l'utilisation de la technologie haptique visant à augmenter le niveau de réalisme d'une simulation influence les résultats des utilisateurs dans une situation de simulation de course à travers l'état de flow et l'état décisif?

Les résultats énoncés ici représentent la performance de conduite perçue, la performance réelle, ainsi que l'espérance de succès, c'est-à-dire la performance prévue suite à une utilisation continue.

Ce mémoire comprend un seul article qui présente en détail l'expérience en laboratoire brièvement décrite ci-dessus - une expérience ayant eu lieu avec le Tech3Lab et impliquant 25 participants volontaires. La première partie de cet article fait le sommaire d'une revue de littérature sur le domaine du sport électronique, et les états psychologiques sous-jacent à une performance optimale dans un contexte de sport. Cette revue de la littérature a été effectuée dans le but de bien comprendre les différentes relations qui peuvent relier le niveau de réalisme d'un système haptique avec la performance de course. La deuxième partie de l'article présente en détail la méthodologie employée et les résultats obtenus. Ces résultats sont ensuite interprétés et discutés en fonction de la littérature académique concernée. Finalement, la dernière partie de l'article, ainsi que la conclusion du mémoire présentent les implications pratiques et théoriques des résultats de ce projet.

1.4 Aperçu général de la structure du mémoire

Le cadre de cette étude est introduit dans ce premier chapitre, notamment par la contextualisation des concepts-clés. La chapitre suivant permettra d'ancrer le cadre conceptuel à travers une revue de littérature. Celui-ci se concentrera également sur la définition conceptuelle des variables principales d'intérêt.

Le troisième chapitre est consacré à l'article scientifique. Après une synthèse de la littérature, celui-ci détaille la méthodologie et les résultats permettant de répondre à aux questions de recherche. À partir de la manipulation du niveau de réalisme d'une simulation vibro-cinétique, cet article illustre les différents effets que la technologie haptique peut avoir sur la performance d'un pilote automobile dans un contexte de simulation. Également, deux médiateurs sont pris en compte par cette étude, à savoir les états mentaux sous-jacents à une performance optimale, l'état de *flow* et l'état décisif. Cet article se conclut sur une discussion illustrant les principales contributions à la recherche fondamentale ainsi que les implications pratiques qui en découlent.

1.5 Contribution et responsabilité individuelle

L'implication de l'étudiant est représentée dans le tableau ci-dessous. Celui-ci synthétise les contributions apportées par l'étudiant durant le projet de recherche au sein du Tech3Lab dans le cadre de son mémoire de recherche.

Tableau 1: Contribution de l'étudiant aux étapes du projet de recherche

Étapes	Contribution
Définition des requis	Définition de la question de recherche et de la problématique - 75% - Contextualisation de la problématique élaborée en collaboration avec un partenaire industriel - Traduction des besoins du partenaire industriel en questions de recherche et définition de la problématique
Revue de littérature	Élaboration de la revue de littérature - 90% - Identification de la littérature existante sur le sujet - Aide des co-auteurs sur l'identification des sujets de recherche - Définition des échelles et mesures à utiliser lors de l'étude - Aide du laboratoire concernant les outils physiologiques et utilisation de ressources déjà établies. Rédaction de la revue de littérature - 100%
Demande de certificat d'éthique de la recherche	Rédaction de la demande au CER et des modifications de projet par la suite - 90% - L'équipe du laboratoire de recherche a fait une relecture de la demande avant la soumission
Design expérimental	Conception du design expérimental et protocoles de test - 80% Concevoir le protocole d'expérimentation - 80% - L'équipe du laboratoire de recherche a recommandé

	un protocole d'utilisation de l'outil physiologique - Organiser la salle de collecte chez le partenaire - 0% - Installer le matériel lors des collectes de données
Recrutement des participants	Rédaction du questionnaire de recrutement - 75% - Le questionnaire de recrutement a été fait en collaboration avec l'équipe de recherche du laboratoire Recrutement et gestion des participants - 20% - Recrutement par le partenaire industriel, effectué en externe - Les données des participants ont été anonymisées par le laboratoire de recherche - Les participants potentiels ont été filtrés selon leur expertise par le partenaire - Les participants sélectionnés ont été contacté par courriel avec l'aide d'un assistant de recherche
Prétests et collecte des données	Responsable des opérations lors des prétests - 100% - Tous les prétests ont été effectués par l'auteur Responsable des opérations lors de la collecte de données - 100% - Présence lors de 100% du processus de collecte
Extraction et transformation des données	Extraction et mise en forme des données en préparation à l'analyse - 100%
Analyse des données	Analyses statistiques - 90% - Aide de l'équipe et du statisticien du laboratoire de recherche pour le traitement des données
Rédaction	Écriture de l'article du mémoire - 100% - Rédaction autonome avec corrections et pistes d'amélioration apportées par les coauteurs

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Chapitre 2: Revue de la littérature

Ce chapitre vise à ancrer le cadre conceptuel sur lequel s'appuie l'article de recherche présenté dans le chapitre 3. L'analyse de la littérature permet de définir les concepts clés de cette étude: le niveau de réalisme, la performance perçue et réelle ainsi que l'espérance de succès. L'étude incorpore également les variables pouvant influencer la relation entre le niveau de réalisme et la performance à travers une variable modératrice, à savoir les états psychologiques sous-jacent à une performance optimale (l'état de *flow* et l'état décisif).

2.1 Méthodologie

La méthodologie adoptée pour la recherche dans le cadre de cette revue de la littérature s'est appuyée sur une stratégie rigoureuse visant à identifier et sélectionner les publications les plus pertinentes concernant la simulation, la technologie haptique et la performance sportive. Cette stratégie s'appuie sur une exploration approfondie des bases de données spécialisées dans le domaine des technologies de l'information et de l'interaction humain-ordinateur, incluant notamment *Web of Science*, *ACM Digital Library*, *IEEE Xplore*, *ScienceDirect* et *SpringerLink* et *Google Scholar*. Ce dernier a servi de point de départ pour son accès étendu à un large éventail de publications.

Les mots clés ont été catégorisés en quatres groupes principaux: les états psychologiques optimaux, les caractéristiques de la simulation, la performance et la technologie haptique. Ces termes ont été combinés avec des mots clés contextuels tels que “virtual environment”, “esports”, ou “simulation” pour affiner la recherche. Un accent particulier a été mis sur les publications récentes, datant des cinq dernières années, pour assurer l'actualité des données recueillies.

L'évaluation des articles s'est basée sur l'intérêt du titre, le nombre de citations, et une lecture attentive du résumé. La bibliographie des articles sélectionnés a permis d'identifier d'autres publications potentiellement pertinentes. Cette approche itérative a été enrichie par l'utilisation de la fonction de recherche avancée sur *Google Scholar*, permettant de découvrir des travaux citant les articles initialement sélectionnés.

Pour organiser efficacement la recherche, les requêtes effectuées sur chaque base de données ont été conservées et une bibliothèque de définitions clés liées à la thématique de recherche a été compilée. Cette démarche s'inscrit dans une volonté de systématiser l'accumulation des connaissances, tenant compte de la diversité des définitions rencontrées. En suivant les recommandations de Webster and Watson, 2002, une matrice conceptuelle a été élaborée pour synthétiser les différents construits étudiés dans la littérature.

Cette méthode de recherche, bien que non systématique, a permis de couvrir de manière exhaustive les mots-clés essentiels liés au sujet, et d'explorer une variété d'auteurs et de publications pertinentes.

2.2 Contexte - Les sports électroniques

L'émergence des sports électroniques, et plus spécifiquement le domaine de la simulation de course automobile, a marqué une transformation dans le paysage des jeux compétitifs et des sports numériques. Les sports électroniques ont évolué pour devenir un phénomène mondial, avec une croissance exponentielle, culminant à une industrie de plusieurs milliards de dollars et attirant une audience de plusieurs centaines de millions (Statista, 2023; Zhang and Liu, 2022). En raison de cet engouement, la communauté scientifique montre un intérêt croissant (Cranmer et al., 2021), commençant à développer des recherches avec des objectifs variés et dans plusieurs domaines scientifiques qui permettent une contextualisation, une évaluation, une amélioration ou un développement de cette nouvelle modalité sportive (Hallmann and Giel, 2018; Pluss et al., 2019; Sanz-Matesanz et al., 2023; Tang, 2018). La convergence entre la technologie et le sport présente de nouvelles opportunités d'approfondir les connaissances existantes sur les sports traditionnels (Chikish et al., 2019), avec le potentiel d'incorporer et d'exploiter des technologies existantes pour créer une nouvelle expérience (Cranmer et al., 2021)

2.3 Le rôle de la simulation dans l'entraînement

Les simulations sont largement utilisées pour l'entraînement dans les sports électroniques comme la simulation de course (Sturm, 2014). Reconnues au-delà du divertissement (Fleming and Sturm, 2014), elles servent à la formation des pilotes, l'élaboration de stratégies et même le développement de voitures (Sturm, 2019; Tudor, 2020).

Les avantages des simulateurs dans un contexte de formation sont multiples (de Winter et al., 2012). Les simulations offrent un environnement sûr, contrôlé et hautement personnalisable, ce qui permet aux joueurs de s'entraîner et d'affiner leurs compétences sans les risques ou les contraintes associés aux courses réelles (de Winter et al., 2012; Kirkman et al., 2014). Grâce à ces plateformes virtuelles, les joueurs peuvent expérimenter un large éventail de scénarios de course, de conditions de piste et de situations de compétition, ce qui est indispensable pour développer des compétences de prise de décision rapide. De plus, la possibilité de s'entraîner à plusieurs reprises à des manœuvres spécifiques permet d'améliorer les compétences de manière très ciblée, ce qui peut être souvent difficile à reproduire dans des environnements physiques (Flach et al., 2008). La nature de ces simulations offre également un retour d'information précieux, permettant aux joueurs d'analyser et d'ajuster leurs performances avec précision, grâce aux données télémétriques, une source d'informations considérée comme la plus importante par les ingénieurs du sport automobile (Bugeja et al., 2017; de Winter et al., 2012).

2.4 Le réalisme en simulation

Cependant, les simulateurs ont aussi certaines limites, notamment en ce qui concerne la fidélité d'un simulateur, c'est-à-dire le degré auquel le simulateur reproduit les caractéristiques de l'environnement réel (Young and Lenn, 2017). Afin d'être efficaces, les simulations utilisées à des fins de formation doivent tendre à refléter fidèlement la tâche et l'environnement réel, afin de susciter des actions réalistes de la part des utilisateurs (Harris et al., 2020). Le niveau de fidélité aura un impact sur le réalisme de l'expérience, et sur le sentiment d'immersion de l'utilisateur (Cummings and Bailenson, 2016; Gerling et al., 2013; Nabiyouni et al., 2015; Witmer and Singer, 1998). Par définition, une simulation est une représentation de la réalité, et même s'il n'y a pas de prérequis indiquant qu'un simulateur devrait tendre à répliquer précisément un environnement réel, il est tout de même nécessaire qu'il comporte une certaine dimension d'interaction (Young and Lenn, 2017). Ainsi, la notion de réalisme est inhérente à la définition même de la simulation.

Un haut niveau de fidélité d'un simulateur est bénéfique à des fins d'entraînement (de Winter et al., 2009; Greenberg and Blommer, 2011), cette fidélité peut aider à améliorer le sentiment d'immersion de l'utilisateur et le convaincre qu'ils sont bel et bien dans un environnement réaliste, l'encourageant ainsi à adopter des comportements réalistes (Mullen et al., 2011; Risto and Martens, 2014; Stanney et al., 1998).

Afin d'accentuer la fidélité d'un simulateur, diverses stratégies sont communément utilisées, en incorporant du retour audio, visuel ou haptique. Les systèmes qui intègrent un retour haptique permettent d'augmenter la fidélité d'une simulation, mais seulement si intégré efficacement

(Stedmon et al., 2009). Un léger décalage entre ce qui est présenté à l'écran et ce qui est ressenti par l'utilisateur pourrait engendrer le mal du simulateur (*cybersickness)*, et avoir un impact négatif sur l'efficacité de l'entraînement (Mourant and Thattacheny, 2000). Des simulateurs de faible fidélité peuvent engendrer des comportements irréalistes et avoir un impact sur la motivation des utilisateurs (de Winter et al., 2012).

2.5 La technologie haptique pour augmenter le niveau de réalisme

La technologie haptique joue un rôle crucial dans la création d'environnements réalistes et immersifs, améliorant l'expérience globale et l'efficacité de l'entraînement en simulation. La technologie haptique fait référence à l'utilisation de mécanismes de retour d'information tactile qui simulent le sens du toucher, offrant ainsi une expérience plus authentique et plus immersive (Scacchi, 2018; Sreelakshmi and Subash, 2017).

L'utilisation du retour haptique dans les environnements virtuels améliore l'immersion, le réalisme et le plaisir de l'utilisateur (Daneels et al., 2018; Elson et al., 2014). La fidélité haptique est utilisée comme une caractéristique objective pour décrire la qualité d'un système avec un retour haptique. Elle est utilisée pour représenter la capacité du système à reproduire de manière réaliste les expériences haptiques, et a le potentiel d'augmenter la perception du réalisme pour l'utilisateur (Muender et al., 2022). Cependant, la fidélité haptique ne décrit pas la manière dont l'utilisateur vivra ou percevra l'expérience haptique, car elle ne tient compte que du degré de réalisme de la technologie elle-même. Ainsi, il devient important de s'intéresser également à la perception du réalisme de la part de l'utilisateur.

La perception du réalisme fait référence à la manière dont l'utilisateur perçoit l'intégration transparente et intuitive des éléments numériques et du monde physique dans un environnement virtuel (Chen and Lin, 2022). Les simulations utilisées à des fins de formation bénéficient grandement d'un simulateur réaliste (de Winter et al., 2009; Greenberg and Blommer, 2011), car il peut contribuer à améliorer le sentiment d'immersion de l'utilisateur et le convaincre qu'il se trouve effectivement dans un environnement réaliste, ce qui l'encourage à adopter des comportements réalistes (Slater and Wilbur, 1997).

Dans un contexte de simulation de course automobile, cette technologie peut contribuer à recréer un environnement réel au sein d'une simulation, en joignant le virtuel au réel. Les simulateurs de conduite engendrent une validité comportementale, où les comportements correspondent à ce qui serait attendu sur la route réelle (Mullen et al., 2011). Cette technologie est intégrée à des équipements tels que les volants, les pédales et les sièges afin de reproduire les sensations physiques de la course automobile réelle. En reproduisant les sensations complexes de la conduite d'une voiture de course, le retour haptique permet de bonifier l'expérience (Bugeja et al., 2017). Par exemple, les volants équipés de mécanismes de retour haptique peuvent transmettre les nuances de la surface de la route, la dynamique du véhicule et même les niveaux d'adhérence des pneus (Bugeja et al., 2017). De plus, les sièges et les pédales haptiques fournissent des signaux physiques qui s'alignent sur les événements du jeu, tels que la texture de la piste, l'accélération, les forces de freinage et les collisions.

2.6 Avantages de la technologie haptique en simulation de course

L'utilisation du mouvement dans un simulateur de course peut grandement améliorer l'expérience des utilisateurs et fournir des avantages cruciaux en termes de performances lorsque la perception de l'accélération est importante (Young and Lenn, 2017), comme c'est le cas avec la simulation de course. Cette technologie permet donc aux joueurs de développer une compréhension plus intuitive de la façon dont les différents véhicules réagissent dans diverses conditions, une compétence inestimable dans les courses virtuelles et réelles. Ces informations sensorielles sont essentielles pour développer la conscience de la situation et les réflexes d'un pilote (Klarica, 2001). En ressentant le comportement de la voiture grâce à ces données haptiques, les joueurs peuvent affiner leur temps de réaction et leurs capacités de prise de décision. L'utilisation de la technologie haptique dans un contexte de simulation de course permet de combler l'écart entre l'expérience de course physique et virtuelle. Elle permet d'entraîner la mémoire musculaire et affiner ses compétences motrices (Sigrist et al., 2013), des capacités qui sont directement transférables dans un scénario de conduite réelle. Pour les pilotes professionnels, cette technologie constitue un outil d'entraînement inestimable qui reproduit fidèlement les sensations physiques et tactiles d'un circuit de course réel (Calleo et al., 2023). La technologie haptique illustre parfaitement la manière dont les innovations numériques peuvent avoir un impact tangible autant dans le domaine virtuel que réel.

La relation complexe entre le retour de force haptique et l'expérience de l'utilisateur a des implications significatives pour les concepteurs de systèmes interactifs. L'interaction avec la technologie haptique suscite de plus en plus l'intérêt des chercheurs qui s'intéressent à la relation entre les technologies numériques et les sens humains (Song and Fu, 2019). En adaptant le retour d'information haptique au traitement d'informations sensorielles de l'utilisateur, les concepteurs peuvent améliorer considérablement l'immersion et l'interaction avec l'utilisateur. Il est particulièrement intéressant de comprendre le potentiel de certaines rétroactions sensorielles et leurs influences sur l'expérience de l'utilisateur.

2.7 La performance en sports électroniques

Considérant que le niveau de fidélité d'un système haptique peut avoir un impact sur l'expérience de l'utilisateur, il est essentiel de prendre en compte les aspects psychologiques qui sous-tendent les performances dans des environnement virtuels, et ainsi, de comprendre par quels mécanismes l'expérience de l'utilisateur, modelée par la fidélité d'un système haptique, influencera à son tour la performance.

Dans un contexte sportif, la performance est utilisée comme un indicateur clé de la réussite d'un athlète, et de sa progression, qui constitue souvent une source d'évaluation (Killham et al., 2018). Comme dans tout autre domaine sportif, l'évaluation des performances dans un contexte de simulation de course est essentielle pour comprendre les progrès des athlètes et l'obtention des résultats escomptés (Pedraza-Ramirez et al., 2020).

Un des axes de recherche développés autour du sport électronique se concentre notamment sur ses similarités et ses différences avec les sports traditionnels (Sanz-Matesanz et al., 2023). Malgré la distinction nette entre le physique et le numérique, ces deux domaines partagent de nombreux aspects, tels que la nature compétitive, les méthodes d'entraînement, et les critères de mesure de performance (Pedraza-Ramirez et al., 2020). En sports électroniques, une performance optimale nécessite de combiner certaines habiletés motrices avec les exigences cognitives spécifiques au sport (Pluss et al., 2019). Les recherches distinguent les joueurs professionnels des amateurs par des capacités telles que la résolution de problèmes (Oei and Patterson, 2014; Vallett et al., 2013), une concentration visuelle et attentionnelle accrue (Lewis et al., 2011), une meilleure perception spatiale (Vallett et al., 2013) et une réactivité plus rapide aux stimuli (Shawn Green et al., 2012).

2.8 Les facteurs qui contribuent à la performance

Tout comme dans les sports traditionnels, les performances en sports électroniques sont affectées par les capacités tactiques et cognitives (Nagorsky and Wiemeyer, 2020), ce qui inclut la réflexion stratégique et la prise de décision. Ensuite, la coordination et l'habileté sont essentielles, car elles nécessitent des interactions sensori-motrices précises avec les interfaces de jeu (Nagorsky and Wiemeyer, 2020). Ces compétences comprennent également la conscience spatiale et l'adaptation rapide à l'environnement virtuel dynamique (Voss et al., 2010). La capacité à prédire les actions et les événements dans un jeu est souvent mentionnée comme une composante importante d'un jeu réussi (Fanfarelli, 2018). La résilience mentale est un autre facteur essentiel. Les joueurs doivent faire preuve de stabilité émotionnelle et d'un état d'esprit compétitif pour naviguer dans les scénarios à haute pression typiques des sports électroniques (Himmelstein et al., 2017; Lee and Schoenstedt, 2011).

Les états mentaux présentent un grand intérêt dans le domaine du sport et de l'exercice physique, étant associés à une motivation intrinsèque et un sentiment de bien-être, et pourraient mener à une meilleure performance sportive (Swann et al., 2022). Ces états psychologiques jouent donc un rôle indispensable dans la compréhension des performances sportives. De plus, les athlètes, quel que soit leur niveau de compétition, s'efforcent toujours à se surpasser et atteindre de nouveaux niveaux de performance, ce qui fait du sport un contexte idéal pour étudier les états psychologiques optimaux (Kimiecik and Jackson, 2002). Toutefois, le rôle des états psychologiques reste encore méconnu pour un contexte aussi spécifique que les sports électroniques (Pedraza-Ramirez et al., 2020).

Si la technologie haptique permet de créer un lien tangible avec le monde virtuel de la course, comprendre et atteindre ces états psychologiques optimaux est essentielle pour tirer parti de ces avancées technologiques et obtenir des performances supérieures.

2.9 L'état de flow

L'expérience optimale la plus étudiée dans le sport est le *flow*, pour ses bénéfices associés à la performance (Csikszentmihalyi, 1990, 1975). Ce concept central de la psychologie positive est une zone mentale d'immersion profonde et de concentration accrue, caractérisé par une altération de la perception du temps, un sentiment de facilité et l'impression d'être en contrôle de la situation

(Nakamura and Csikszentmihalyi, 2002). L'état de *flow* est étudié dans les sports depuis de nombreuses années, et a même été le sujet de plusieurs revues systématiques (Boudreau et al., 2020; Harris et al., 2021; Jackman et al., 2021; Triberti et al., 2021; Valinatajbahnamiri and Siahtiri, 2021). Ces recherches ont permis de fournir une synthèse des connaissances existantes sur l'état de *flow*, comprendre les facteurs qui facilitent son apparition, et les résultats de cet état. À travers ces revues systématiques, les chercheurs rapportent que l'expérience du *flow* est associée avec des performances optimales ou améliorées, ainsi qu'un sentiment d'accomplissement et de bien-être (Boudreau et al., 2020; Csikszentmihalyi, 1975; Harris et al., 2021). Compte tenu des avantages qui y sont associés, les interventions connues pour induire les expériences de *flow* sont très appréciées par les athlètes, les entraîneurs et les praticiens (Swann et al., 2018).

2.10 Les bénéfices de l'état de flow

Le concept de *flow* est régulièrement décrit comme étant sous-jacent à des performances supérieures ou améliorées dans la littérature sportive (Harris et al., 2021; Jackson and Csikszentmihalyi, 1999; Norsworthy et al., 2017; Swann et al., 2017a). En favorisant la concentration et en poussant les athlètes jusqu'à leurs limites, cet état mental permet l'amélioration des performances (Jackson and Csikszentmihalyi, 1999) L'état de *flow* contribue de manière significative à l'amélioration des performances en facilitant les conditions psychologiques optimales pour exécuter les tâches de manière efficace et efficiente (Harris et al., 2021; Jackson and Csikszentmihalyi, 1999; Sklett et al., 2018). La concentration focalisée caractéristique de l'état de *flow* pourrait expliquer l'amélioration des performances dans le sport (Harris et al., 2021) et dans les sports électroniques (Campbell et al., 2018). Cet état d'engagement accru permet aux individus de donner le meilleur d'eux-mêmes, ce qui se traduit souvent par des niveaux d'accomplissement supérieurs. Les résultats intrinsèques du *flow*, comme le plaisir et l'engagement émotionnel (Jackson and Csikszentmihalyi, 1999; Valinatajbahnamiri and Siahtiri, 2021) favorise l'épanouissement personnel et le développement des compétences. Dans un contexte de simulation de course, entrer dans cet état permet de maintenir une concentration prolongée, un contrôle précis et une prise de décision rapide, des aspects importants pour la course automobile. Ainsi, le pilote peut espérer obtenir des temps de réaction améliorés, une conscience aiguisée de la situation et une perception intuitive de la voiture et des conditions de course.

2.11 L'état décisif

Des études récentes sur les états psychologiques sous-jacents à la performance sportive ont révélé que l'état de *flow* ne représente que partiellement les expérience d'états optimaux (Harris et al., 2021), et que la performance des athlètes ne peut être attribuée à l'état de *flow* uniquement. En effet, l'état de *flow* est décrit comme l'une des deux voies possibles pour améliorer les performances athlétiques. L'autre voie, plus délibérée, est décrite comme l'état décisif (traduction du terme anglais *clutch*) (Swann et al., 2017a, 2016). Bien que ces deux états partagent de nombreuses caractéristiques, d'autres éléments de cet état semblent incompatibles avec certaines caractéristiques traditionnellement associés à l'état de *flow* (Houge Mackenzie et al., 2023). Par exemple, l'état de *flow* est généralement associé à un sentiment de contrôle sans effort et une absence de pensées analytiques, alors que l'état décisif serait caractérisé par des efforts pour exercer un contrôle et des pensées analytiques délibérées (Swann et al., 2019). Ainsi, l'état décisif serait un état distinct du *flow* qui fait référence à l'état mental d'un individu lorsqu'il est soumis à la pression d'être performant où l'obtention d'un résultat significatif est important (Swann et al., 2017a). Il est proposé que l'état de *flow* et l'état décisif se produisent dans des contextes distincts et par le biais de processus différents, mais que tous deux pourraient mener à une performance supérieure (Boudreau et al., 2022; Houge Mackenzie et al., 2023; Swann et al., 2017). Dans un état décisif, les athlètes réalisent l'importance du contexte de la performance, et la nécessité de fournir une performance supérieure pour surmonter les exigences de la situation (Swann et al., 2017a). Dans un contexte de simulation de course, l'état décisif peut potentiellement se produire lors de dépassements clés, dans les derniers tours d'une compétition, ou encore lors de la récupération d'erreurs. Cet état psychologique permet aux pilotes de réaliser des performances exceptionnelles lorsque les enjeux sont élevés (Swann et al., 2017a), en prenant des décisions et en effectuant des manœuvres qui peuvent être décisives pour l'issue de la course.

L'état décisif est caractérisé par une concentration complète et délibérée sur la tâche, un effort intense et une conscience accrue des exigences de la situation (Swann et al., 2017c). Dans cet état, les athlètes décrivent une excitation accentuée due à l'intensité de l'effort fourni. De plus, l'exécution des compétences spécifiques à la situation se déroule de manière automatique, mais les athlètes mentionnent être beaucoup plus conscients des exigences de la situation et des conséquences d'une réussite ou d'un échec (Swann et al., 2017c).

Ainsi, explorer l'état décisif en plus de l'état de *flow* permet d'avoir une compréhension plus globale des mécanismes sous-jacents à la performance optimale (Swann et al., 2017a). Ces états sont fondamentaux pour l'entraînement en simulation de course. Ils sont non seulement cruciaux pour les performances de haut niveau, mais ils améliorent également l'expérience globale de la course. Alors que les outils technologiques tels que le retour haptique améliorent la connexion physique et sensorielle à l'environnement de course virtuelle, la compréhension de ces états psychologiques optimaux permet aux pilotes d'exploiter pleinement leurs compétences et la technologie à leur disposition, contribuant à la fois à la réussite en compétition et à l'épanouissement personnel dans le sport.

2.12 The Integrated Model of Flow and Clutch States

Le modèle théorique *The Integrated Model of Flow and Clutch States* (voir Figure 1) (Swann et al., 2017a) offre une perspective plus complexe et plus fine des états psychologiques sous-jacents à la performance en décortiquant les états psychologiques vécus par les individus. Ce modèle découle de récentes études qualitatives qui ont révélé une perspective élargie des états psychologiques sous-jacents à la performance en sport (Swann et al., 2017a, 2016). Développé initialement à partir d'entretiens avec des golfeurs professionnels (Swann et al., 2016), ce modèle a été affiné grâce à des études portant sur une diversité d'athlètes (Jackman et al., 2020, 2017; Swann et al., 2019, 2017a, 2017b).

Ce modèle intégré reconnaît la nature distincte de l'état de *flow* et de l'état décisif malgré des caractéristiques qui se chevauchent, en indiquant que ces deux états ne peuvent être expérimentés simultanément, bien qu'ils puissent survenir au cours de la même activité avec des transitions possibles de l'un à l'autre (Swann et al., 2017a). Ce modèle délimite les antécédents, les facilitateurs, les dimensions et les résultats associés aux états de *flow* et décisif.

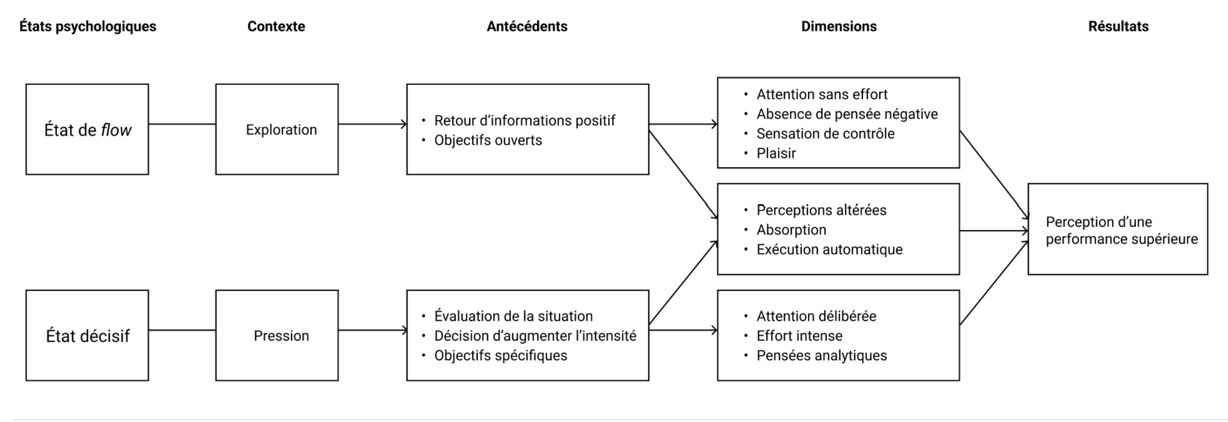

Figure 1: Modèle intégré de l'état de *flow* et décisif, basé sur les travaux de Swann et al., 2017a

2.13 Les dimensions de l'état de flow et de l'état décisif

Les états de *flow* et décisif, deux états suggérés comme étant distincts, présentent des dimensions caractéristiques qui reflètent la complexité des expériences psychologiques dans le sport.

L'état de *flow* est caractérisé par une attention sans effort, où les athlètes se sentent complètement absorbés dans l'activité sans être entravés par des pensées critiques ou négatives (Swann et al., 2017c). L'expérience du *flow* est marquée par une sensation de facilité, où les actions semblent se dérouler automatiquement et sans effort (Swann et al., 2017c). Les athlètes en état de *flow* éprouvent un plaisir immédiat dans l'activité elle-même, avec un sentiment de contrôle et un retour d'information positif sur leurs progrès (Swann et al., 2017a).

En revanche, l'état décisif se caractérise par un effort maximal et une concentration intense (Swann et al., 2017a), plutôt qu'une expérience sans effort, caractéristique de l'état de *flow*. Les athlètes en état décisif sont pleinement conscients des exigences de la situation et des conséquences de la réussite ou de l'échec (Swann et al., 2017c). Bien que l'exécution des compétences puisse être automatique, il y a une conscience accrue et des pensées analytiques centrées sur l'atteinte d'objectifs spécifiques (Swann et al., 2017c). Les performances en état décisif sont souvent associées à une excitation accrue et à un effort pour exercer un contrôle, plutôt qu'à un sentiment de contrôle naturel observé dans le *flow*.

Les deux états partagent des caractéristiques telles que l'exécution automatique des compétences, des perceptions altérées (comme un sens du temps modifié), une absorption profonde dans l'activité et une confiance accentuée (Swann et al., 2017c). Ces caractéristiques communes soulignent la nature immersive et intense de ces expériences, mais leurs distinctions résident dans l'orientation de l'attention, la qualité de l'expérience, et la nature de la motivation. Le *flow* est marqué par une harmonie et une aisance, tandis que l'état décisif est défini par une intensité et une focalisation consciente sur des objectifs spécifiques et des résultats cruciaux (Swann et al., 2017a).

2.14 Les antécédents de l'état décisif

L'état décisif, contrairement au *flow,* se manifeste de manière relativement soudaine, en réponse à une évaluation des exigences de la situation. Cette appréciation conduit les athlètes à un processus de mise en marche rapide, caractérisé par une augmentation de l'effort et de l'intensité. L'état décisif est déclenché par des contextes de pression, souvent à la fin d'événements (Swann et al., 2019) où l'atteinte d'un résultat important est en jeu, avec la décision de diriger l'attention et les efforts vers un objectif précis (Jackman et al., 2020; Swann et al., 2017a). L'état de *flow* et l'état décisif ont été rapportés de manière cohérente à travers une gamme d'activités sportives relativement diverses (Swann et al., 2019), ce qui renforce l'idée que ces états mentaux peuvent survenir dans des contextes variés.

Un facteur important dans l'apparition de l'état décisif est la nature des objectifs poursuivis (Schweickle et al., 2017). Les athlètes définissent des objectifs fixes spécifiques lorsqu'ils entrent en état décisif, contrairement aux objectifs ouverts plus exploratoires qui conduisent au *flow* (Schweickle et al., 2017; Swann et al., 2017c). Ces objectifs fixes nécessitent une décision consciente d'augmenter l'effort et l'intensité pour les atteindre, ce qui marque l'entrée dans un état décisif. Ces constatations indiquent que les objectifs clairement définis et orientés vers une performance précise sont essentiels pour déclencher un état décisif, mettant en évidence le rôle crucial de la fixation d'objectifs dans les performances sous pression.

2.15 Les résultats des états de flow et décisif

Les états de *flow* et décisif ont également certains résultats en commun, ces deux états ont été liés à de multiples résultats positifs, autant psychologiques que comportementaux (Houge Mackenzie et al., 2023). Ils mènent tous deux à des récompenses intrinsèques, dont un sentiment d'accomplissement et de satisfaction après l'expérience (Swann et al., 2017a), et une perception d'excellente performance (Houge Mackenzie et al., 2023; Schweickle et al., 2017). Suite à des analyses qualitatives, les athlètes ayant vécus les états de *flow* et décisif durant une activité sportive ont rapporté avoir eu l'impression de bien performer (Swann et al., 2019, 2017c, 2016).

Toutefois, une différence notable réside dans le ressenti post-expérience de chaque état. Après avoir vécu un état de *flow*, les athlètes rapportent se sentir énergisés, capables de poursuivre ou de recommencer l'activité sans difficulté (Boudreau et al., 2022; Houge Mackenzie et al., 2023; Jackman et al., 2019). En revanche, l'état décisif est souvent suivi d'un sentiment d'épuisement dû à l'intensité et à l'effort conscient requis pendant ces performances (Swann et al., 2017c).

2.16 L'état décisif dans la littérature

Les recherches récentes ont permis d'obtenir une meilleure distinction entre l'état de *flow* et l'état décisif, révélant des caractéristiques uniques à chacun. Cependant, l'absence d'outils de mesure spécifique pour distinguer clairement ces deux états représente un défi méthodologique. La littérature récente s'est intéressée au manque de mesure psychométrique validé pour capturer l'état décisif. Majoritairement, les études sur l'état décisif ont privilégié une approche qualitative (Sánchez Vara et al., 2023; Schweickle et al., 2021; Swann et al., 2022), mettant en avant les thèmes importants décrivant les expériences vécues d'état de *flow* et d'état décisif, leurs moments d'occurrence et les mécanismes sous-jacents.

Ces recherches ont réussi à établir des distinctions claires entre le *flow* et l'état décisif. Les descriptions fournies par les athlètes différencient nettement ces deux états, soulignant des variations dans la façon dont ces états étaient vécus, et les circonstances de leur apparition (Jackman et al., 2020; Schweickle et al., 2017, 2023, 2021; Swann et al., 2022, 2016). Cette approche qualitative a enrichi notre compréhension des nuances entre le *flow* et l'état décisif, tout en mettant en lumière le besoin de développer des instruments de mesure plus précis pour ces états psychologiques (Swann et al., 2019, 2017a).

Des tentatives ont été faites pour quantifier ces états. Schweickle et al., 2017 et ses collègues ont développé une mesure dichotomique afin de capturer indépendamment l'état de *flow* et l'état décisif, basé sur les différences les plus évidentes entre les deux états, telles que rapportées qualitativement par les athlètes (Swann et al., 2017a, 2016). Cette étude a révélé que certaines recherches antérieures sur le *flow* qui auraient manipulé l'équilibre défi-compétences pourraient en fait avoir mesuré l'état décisif (Schweickle et al., 2017). De leur côté, Jackman et al., 2020, ont tenté d'utiliser des échelles de mesure validées pour mesurer le *flow*, pour identifier l'occurrence potentielle de *flow* et/ou d'état décisif. Toutefois, ces outils, conçus initialement pour le *flow*, ont été critiqués pour leur amalgame potentiel des deux états dans les descriptions des items (Swann et al., 2018).

Des échelles de mesures validées ont été développées en tenant compte des distinctions entre les états de *flow* et décisif, notamment la *New Short Flow Scale* et la *Clutch Scale*, deux échelles de mesure validées dont la cohérence interne a été démontrée (Sánchez Vara et al., 2023). Afin d'obtenir deux échelles de mesures distinctes pour capturer indépendamment ces deux états, les auteurs ont développé une nouvelle échelle de mesure pour l'état décisif dont les items ont été basés sur chaque caractéristique qui distingue l'état décisif de l'état de *flow*, en adéquation avec les travaux de Swan et al. 2016, afin d'assurer une validité discriminante entre ces deux états. Validée avec trois études distinctes, ces deux échelles de mesures permettent de capturer les aspects essentiels de chaque état psychologique (Sánchez Vara et al., 2023).

De plus, les recherches sur l'état décisif se limitent, à notre connaissance, principalement au domaine sportif, sans exploration dans les environnements virtuels, contrairement au *flow.* Cette observation souligne l'opportunité d'étudier ces deux états dans la relation entre la qualité des systèmes informatiques et la performance individuelle, ouvrant des perspectives intéressantes pour la recherche future.

2.17 Les facteurs qui influencent les états psychologiques optimaux

Plusieurs facteurs ont été identifiés comme facilitant l'induction de l'état de *flow,* y compris les conditions environnementales et situationnelles (Swann et al., 2012), telles que la qualité du retour d'information (Palomäki et al., 2021) et le réalisme de l'environnement virtuel (Zumbach et al., 2015). Grâce à l'immersion accrue d'une technologie, il est plus facile pour les utilisateurs d'entrer dans un état de *flow* (Georgiou and Kyza, 2017). Cet aspect renforce la nécessité de comprendre l'influence du réalisme d'un environnement virtuel sur l'expérience de l'utilisateur.

Les états psychologiques optimaux, l'état de *flow* et décisif, jouent un rôle très important dans la compréhension des performances d'un athlète. Des études antérieures ont systématiquement établi un lien entre l'état de *flow* et l'amélioration des performances sportives (Harris et al., 2021; Jackman et al., 2021; Swann et al., 2017a). Cet état mental dans le sport conduit souvent à des bénéfices intrinsèques et à la perception d'une performance supérieure, même si le résultat objectif peut suggérer le contraire (Swann et al., 2022).

En outre, une performance réussie sous pression ne contribue pas seulement à une expérience plus gratifiante et plus agréable pour les athlètes (Otten, 2007), mais il a également été suggéré que c'est le facteur de succès le plus important dans le sport (Mesagno and Mullane-Grant, 2010; Swann et al., 2019, 2016), car les performances décisives ont souvent un impact déterminant sur l'issue d'une compétition (Hibbs, 2010). Lors de l'opérationnalisation du résultat de la performance en relation avec l'état décisif, il est important de prendre en compte l'interprétation subjective des athlètes et de ne pas s'appuyer uniquement sur des indicateurs objectifs (Schweickle et al., 2023).

2.18 La performance subjective et objective

Dans un contexte sportif, afin de saisir pleinement l'étendue de la performance athlétique, il est essentiel de prendre en compte non seulement les résultats tangibles, mais aussi l'interprétation personnelle de ces résultats par les athlètes eux-mêmes (Schweickle et al., 2023). Il peut arriver que des athlètes, malgré une performance objective plus faible, rapportent une meilleure perception de leur performance (Schweickle et al., 2017). Le concept d'espérance de réussite est particulièrement pertinent à cet égard, car il met en évidence le rôle des attentes positives dans le renforcement de l'engagement d'un athlète par rapport à ses objectifs de performance (Wulf and Lewthwaite, 2016). En comprenant et en exploitant les concepts psychologiques de la perception de la performance et de l'espérance de réussite conduit à une approche plus holistique de l'optimisation de la performance sportive.

L'espérance de réussite, ancrée dans la motivation et la confiance en soi, est le jugement anticipatif d'un individu sur sa performance à venir dans une tâche (Wulf and Lewthwaite, 2016; Xiang et al., 2003). Il s'agit d'un jugement subjectif qui précède l'acte, basé sur les expériences passées, la perception de soi et les indices contextuels. Les circonstances qui renforcent les attentes des apprenants quant à leurs performances futures peuvent favoriser encore davantage la réussite, l'amélioration et l'apprentissage (Rosenqvist and Skans, 2015). Dans la littérature sportive, l'amélioration des attentes concernant les performances futures, en particulier la confiance en soi, a été associée au *flow* (Harris et al., 2019; Swann et al., 2012).

En ce sens, la performance peut être considérée comme le résultat objectif d'une activité sportive, ou le résultat perceptuel observé après l'exécution de la tâche. Bien qu'un réalisme accru et des états psychologiques optimaux puissent amplifier l'espérance de succès d'un joueur, il ne garantissent pas une performance supérieure. Il est donc important de considérer ces deux concepts séparément.

2.19 Conclusion

En conclusion, l'objectif de cette étude est de comprendre l'impact des technologies émergentes, en particulier la technologie haptique et les simulateurs, sur la performance dans les sports électroniques. Elle vise également à explorer les mécanismes psychologiques, notamment les états de *flow* et décisif qui influencent la performance dans ces environnements virtuels. Pour se faire, le modèle théorique *The Integrated Model of Flow and Clutch States* sera utilisé pour décomposer et comprendre les différents états psychologiques vécus par les individus dans un contexte de simulation de course. Ce modèle est particulièrement adapté pour examiner l'interaction complexe entre la technologie haptique et la performance. La performance, dans ce contexte, est définie non seulement par la réussite tangible et objective, mais également par l'évaluation subjective des utilisateurs. Malgré la pluralité de recherches sur les simulateurs et la technologie dans les sports électroniques, peu d'études ont exploré en profondeur, à notre connaissance, la relation entre ces technologies avancées, les états psychologiques optimaux et leur influence sur la performance dans le contexte spécifique des sports électroniques. De plus, le concept d'état décisif a été principalement examiné, à notre connaissance, dans le contexte de sports traditionnels et par une approche méthodologique de recherche qualitative.

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Chapitre 3: Article

Enhancing realism in racing simulation: The mediating effects of optimal psychological states between haptic technology and performance[1]

David Tessier, Théophile Demazure, Pierre-Majorique Léger, Jared Boasen, Alexander Karran, Sylvain Sénécal

Abstract

This experimental study investigates the mediating role of flow and clutch states between performance outcome in simulated racing and haptic feedback. Flow state, defined as a total immersion state with heightened concentration, and clutch state, characterized by peak performance under pressure, are key concepts for understanding superior sporting performance. While the use of haptic feedback in virtual environments like simulated racing enhances the immersion and realism, understanding these optimal psychological states enables drivers to fully exploit the technology at their disposal. This research focuses on how the flow and clutch states mediate the relationship between realism enhanced by haptic fidelity and performance outcomes in virtual racing environments. A sample of 25 racing simulation experts participated, completing races using five different car simulators with varying levels of haptic fidelity. The study revealed that flow and clutch states significantly mediate the effect of haptic fidelity on performance and expectancy of success. The research offers new insights into the clutch state, a concept until now only present in traditional sports literature, and performance mechanisms in racing simulation. These results are particularly beneficial for designers and developers, guiding the optimization of haptic systems to improve user interaction and performance in virtual contexts.

[1] Cet article est en préparation pour soumission au journal *International Journal of Human-Computer Interaction*

1.1 Introduction

Virtual simulations are essential to sports training (Cecil et al., 2021; Checa and Bustillo, 2020; Sadeghi Milani et al., 2024; Walch et al., 2017; Zahabi and Abdul Razak, 2020), offering a safe and controlled environment for skill development without real-world risks (de Winter et al., 2012). They accurately replicate real-world dynamics (Scacchi, 2018), establishing themselves as valid training tools (Fleming and Sturm, 2014). For example, professional teams in motor racing employ these simulations for driver training, strategic planning, and driver performance analysis (Bugeja et al., 2017; de Winter et al., 2012; Knox, 2011; Sturm, 2019; Tudor, 2020).

Simulating realistic conditions enhances complex skill learning (Le Noury et al., 2021; Oagaz, 2021) and yields transferable improvements comparable to real-world training (Markwell, 2023; Harris, 2020). Beyond the performance aspect, simulations should also favor psychological states contributing to sports training, as athletes' performance is fundamentally tied to their mental states (Jackson, 2001). These states are critical for performance, motivation, and well-being (Swann et al., 2022), raising the question of how virtual simulations can foster these optimal psychological states to positively impact training and performance.

The literature suggests that flow state plays a crucial role in performance, a concept well-documented within sports science (Csikszentmihalyi, 1975; Harris et al., 2021; Jackman et al., 2021; Swann et al., 2017a) and virtual simulation training (Oliveira et al., 2023; Rissler et al., 2018). Studies have shown that technology-mediated activities frequently facilitate flow experiences (Triberti et al., 2021; Uhm et al., 2023; Wang et al., 2023). Flow is characterized by a state of deep immersion and heightened concentration where individuals feel a perfect synergy between their skills and the task at hand, often accompanied by a loss of sense of time (Nakamura and Csikszentmihalyi, 2002). This state helps to understand the experiential aspects of athletes during sports activity (Csikszentmihalyi, 1990). Athletes, coaches, and practitioners highly regard interventions to induce flow for their association with optimal performance, a sense of accomplishment, and well-being (Swann et al., 2018; Boudreau et al., 2020; Harris et al., 2021).

However, recent research indicates that the state of flow might not fully explain optimal performance (Harris et al., 2021). A complementary mental state, the clutch state, is increasingly recognized as crucial for peak performance (Swann et al., 2016; Schweickle et al., 2021), particularly during high-pressure moments in competition (Swann et al., 2016; Swann et al., 2017a). The ability to excel under pressure enhances athletes' experience, making it more rewarding and enjoyable (Otten, 2007), and is also a key determinant of success in sports (Mesagno and Mullane-Grant, 2010; Swann et al., 2019, 2016). Performance under pressure is often a decisive factor in competition outcomes (Hibbs, 2010).

Flow and clutch states share certain dimensions, such as automatic execution of skills, altered perceptions, deep absorption, and heightened confidence (Swann et al., 2017c), these two states occur independently (Swann et al., 2017a). However, the flow state is characterized by an effortless experience, the clutch state is characterized by maximum effort and intense concentration (Swann et al., 2017a). In a clutch state, the individual is often very aware of the importance of his performance and what is at stake, unlike in the flow state, where this awareness can be diminished due to immersion in the activity (Swann et al., 2017a).

Because of their distinct but complementary nature, understanding the clutch state, in addition to the flow state, can offer a more comprehensive perspective on the psychological mechanisms that influence high-level performance (Swann et al., 2022), particularly in high-pressure, high-stakes virtual simulation contexts (Jang and Byon, 2019).

In this context, electronic sports offer an ideal field of study for exploring these optimal psychological states. Electronic sports are defined as a type of sport where the actions enabling its development are facilitated by electronic systems (Hamari and Sjöblom, 2017) and reflect the same performance requirements as traditional sports, while offering new avenues for research into the relation between physical and digital components (Pluss et al., 2019).

Racing simulation, a virtual simulation of motor racing, has also followed the popularity of electronic sports, gaining interest for its ability to realistically recreate the intricate details of real-world racing (Paiva, 2015). This blend of authentic racing experiences with advanced technology offers new possibilities for training (Sturm, 2014; Tudor, 2020) and performance analysis (Bugeja et al., 2017; Knox, 2011), and could also enhances the immersive experience of the simulation (Crawford et al., 2019; Sturm, 2019).

Central to this immersive experience is the integration of haptic technology (Kim and Schneider, 2020; Lelevé et al., 2020; Wee et al., 2021), which can help enriching the realism of the simulation by providing adequate tactile feedback that simulates real-world racing (Muender et al., 2022). This technology can help players to develop an intuitive understanding of vehicle dynamics and racing conditions, essential for improving performance in racing (Calleo et al., 2023; Klarica, 2001).

Performance in electronic sports is influenced by both technological aspects, including the quality of haptic feedback (Calleo et al., 2023; Sigrist et al., 2013; Swann et al., 2017), and psychological factors (Nagorsky and Wiemeyer, 2020; Swann et al., 2022; Voss et al., 2010).

It is hypothesized that the increased realism induced by haptic technology can promote deeper immersion for players (Scacchi, 2021b; Sreelakshmi and Subash, 2017), which could make it easier to enter a state of flow (Chen and Lin, 2022) and clutch (Houge Mackenzie et al., 2023).

Consequently, the central problem of this research revolves around the relation between haptic technology, the level of simulation fidelity, the ability to enter flow and clutch states and their impact on performance outcomes in racing simulation, with the following research question:

To what extent does the use of haptic technology increases the level of realism in a simulation and impact users' performance outcome in racing simulation, mediated by the experienced levels of flow and clutch states?

This research aims to provide insight into how technological improvements to game simulations can influence the psychological aspects of the player, ultimately impacting on their performance and experience.

In this paper, we begin by reviewing the existing literature associated with electronic sports performance, haptic technology and optimal psychological states to introduce the main constructs of interest for this study. We conclude from this review that theoretically, haptic fidelity enhances the ability to achieve flow and clutch states, which in turn, improve the performance outcomes, leading to our main hypotheses that these optimal psychological states act as mediators in the relationship between haptic fidelity and performance outcomes. Next, we present the quantitative results of our experiment, which generally support our hypotheses and provide insights into our research questions. Lastly, we discuss the implications and limitations of our research, concluding with a series of recommendations for future research directions. Our results suggest a full mediation of flow and clutch states between haptic fidelity and performance.

1.2 Background

Electronic sports

Having emerged as a multi-billion dollar industry (Statista, 2023; Zhang and Liu, 2022), electronic sports is contributing to the evolution of sporting competition, and also training and athletic performance. This popularity is generating growing interest from the scientific community, which is beginning to develop research with a variety of objectives to contribute to the evaluation and development of this new sporting modality (Pluss et al., 2019; Sanz-Matesanz et al., 2023; Tudor, 2020).

Training simulations

Given the popularity of simulators for training purposes (Fleming and Sturm, 2014; Sturm, 2014), understanding their benefits is crucial for maximizing their potential in enhancing skill development and performance.

The advantages of simulators in a training context are multiple (de Winter et al., 2012), offering a safe, controlled and highly customizable environment, allowing players to train without the risks associated with real racing (de Winter et al., 2012; Kirkman et al., 2014). In simulated racing, this aspect is crucial, where the simulation's fidelity to real racing conditions is of high importance (Young and Lenn, 2017). With these immersive virtual platforms, players can experience a wide range of racing scenarios, track conditions and competitive situations (Xie et al., 2021), which is essential for developing rapid decision-making skills (Chiang et al., 2022; Radhakrishnan et al., 2021). The ability to repeatedly practice specific maneuvers enables skills to be improved in a highly targeted way, which can be often difficult to replicate in physical environments (Flach et al., 2008; Zahabi and Abdul Razak, 2020). Simulations can be an effective training method for skill development, as they contribute to perceptual-motor skills for improving the accuracy and precision of physical movements (Harris et al., 2020; Radhakrishnan et al., 2021). The nature of these simulations also offers valuable feedback, enabling players to analyze their performance precisely, with telemetry data, a source of information considered the most important by motorsport engineers (Bugeja et al., 2017).

Fidelity and realism in simulations

Effective training simulations should aim on accurately reflecting the real task and environment to elicit realistic actions (Harris et al., 2020) The level of fidelity, or the extent to which a simulation recreates the real-world system (Gray, 2019; Harris et al., 2020), will have an impact on the perceived realism of the experience, and on the user's sense of immersion (Harris et al., 2020). A high level of fidelity in a simulator is beneficial for training purposes (de Winter et al., 2009; Gray, 2019; Greenberg and Blommer, 2011; Harris et al., 2020), as this fidelity can help improve the user's sense of immersion and convince them that they are indeed in a realistic environment, thus encouraging them to adopt realistic behaviors (Gray, 2019; Mullen et al., 2011; Risto and Martens, 2014; Stanney et al., 1998).

Haptic technology

Systems that incorporate haptic feedback can increase the fidelity of a simulation, if integrated effectively (Stedmon et al., 2009). Haptic technology is defined as the use of tactile feedback mechanisms that simulate the sense of touch (Muender et al., 2022), offering a more authentic and immersive experience (M. Kim et al., 2020; Scacchi, 2018; Sreelakshmi and Subash, 2017). This technology could help to create realistic and immersive environments, enhancing the overall experience (Daneels et al., 2018; Elson et al., 2014, Nam et al., 2012).

In racing simulation, this technology can help recreate a realistic environment within a simulation. Driving simulators can generate *behavioral validity*, where behaviors correspond to what would be expected on the real road (Mullen et al., 2011). By reproducing the complex sensations of driving a race car, haptic feedback could enhance the experience (Bugeja et al., 2017; Chang et al., 2011). As an example, steering wheels equipped with haptic feedback mechanisms can convey the nuances of the road surface, vehicle dynamics and even tire grip levels (Bugeja et al., 2017). This sensory information is essential for developing a driver's situational awareness and reflexes (Klarica, 2001), as it helps train muscle memory and fine-tune motor skills (Sigrist et al., 2013).

This technology has become an invaluable training tool, faithfully reproducing the physical and tactile sensations of a real racetrack (Calleo et al., 2023).

Performance in electronic sports

In a sporting context, performance is used as a key indicator of an athlete's success, and progression, which is often a source of evaluation (Killham et al., 2018). As in any other sporting domain, performance evaluation in a racing simulation context is essential to understanding athlete progress and the attainment of desired outcomes (Pedraza-Ramirez et al., 2020).

One of the areas of research developed around electronic sports focuses on its similarities and differences with traditional sports (Sanz-Matesanz et al., 2023). Despite the clear distinction between the physical and the digital, these two fields share many aspects, such as the competitive nature, training methods, and performance measurement criteria (Pedraza-Ramirez et al., 2020). In electronic sports, as in traditional sports, optimal performance requires combining certain motor skills with sport-specific cognitive demands (Nagorsky and Wiemeyer, 2020; Pluss et al., 2019).

Psychological states play an indispensable role in understanding excellent sporting performance (Csikszentmihalyi, 1990; Swann et al., 2022). Athletes at all levels of competition are always aiming to surpass themselves and reach new levels of performance, making sport an ideal context to study optimal psychological states (Kimiecik and Jackson, 2002). However, the role of psychological states remains understudied for a context as specific as electronic sports (Pedraza-Ramirez et al., 2020).

Considering that the level of fidelity of a haptic system can have an impact on the user's experience and perceived realism, it is essential to take into account the psychological aspects underlying performance in virtual environments, and thus gaining a better understanding of the mechanisms by which the user's experience, shaped by the fidelity of a haptic system, will in turn influence performance outcomes.

1.3 Theoretical background

Optimal psychological states

A recurring concept in sports literature (Boudreau et al., 2020; Csikszentmihalyi, 1990; Harris et al., 2021; Jackman et al., 2021) and computer-mediated environment (Triberti et al., 2021; Valinatajbahnamiri and Siahtiri, 2021) is flow, for its benefits associated with task performance (Csikszentmihalyi, 1990, 1975). This state of deep immersion and heightened concentration, where individuals feel a perfect synergy between their skills and the task at hand (Csikszentmihalyi, 1990; Nakamura and Csikszentmihalyi, 2002), has been associated with optimal or improved performance, as well as a sense of accomplishment and well-being (Boudreau et al., 2022; Csikszentmihalyi, 1975; Harris et al., 2021). Given the associated benefits, interventions that help stimulate flow experiences are greatly valued by athletes, coaches and practitioners (Swann et al., 2018).

However, recent studies on the psychological states underlying sports performance have revealed that the flow state only partially represents experiences of optimal states (Harris et al., 2021), and that athletes' performance cannot be attributed to the flow state alone. Instead, some authors suggested another, more deliberate path that can lead to enhanced athletic outcomes; the clutch state (Swann et al., 2017a, 2016). Clutch state is characterized by an athlete's ability to deliver peak performance under significant pressure, usually in the pivotal moments of a competition (Swann et al., 2017a). This psychological state could enable drivers to perform better when the stakes are high, making decisions and maneuvers that can be decisive for the outcome of the race.

The Integrated Model of Flow and Clutch States

Recent studies on the flow state have led to the development of *The Integrated Model of Flow and Clutch States* (Swann et al., 2017a). Initially developed from interviews with professional golfers (Swann et al., 2016), this model has been refined through studies of a diversity of athletes (Jackman et al., 2020, 2017; Swann et al., 2019, 2017a, 2017b). These studies explain that flow state only partially represents experiences of optimal states, and that athletes reported two states that underlie superior performance (Swann et al., 2017a, 2016). This model acknowledges the existence of a second distinct psychological state, the clutch state. *The Integrated Model of Flow and Clutch States* (Swann et al., 2017a) offers a more complex and refined perspective on the psychological states underlying performance by deconstructing the psychological states experienced by individuals.

This model represents the antecedents, facilitators, dimensions and outcomes associated with the states of flow and clutch, recognizing their distinct nature, despite overlapping characteristics. These two states cannot be experienced simultaneously, although they can occur during the same activity with possible transitions from one to the other (Swann et al., 2017a).

Flow and clutch states are proposed to occur in distinct contexts and through different processes. Flow state emerge in novel or exploratory scenarios (Doherty and Doherty, 2018; Swann et al., 2016; Tokunaga, 2013; Valinatajbahnamiri and Siahtiri, 2021), where gradual confidence build-up occurs through positive feedback (Ozkara et al., 2017; Peifer et al., 2020), leading athletes to set open goals to engage with the task at hand (Novak et al., 2003; Swann et al., 2017a). The flow state is characterized by effortless attention, where athletes feel completely absorbed in the activity without being distracted by critical or negative thoughts (Peifer et al., 2020; Swann et al., 2017c), and where actions seem to happen automatically and effortlessly (Swann et al., 2017c). Athletes in flow report feelings of satisfaction and emotional engagement (Valinatajbahnamiri and Siahtiri, 2021), often leading to superior outcomes (Harris et al., 2021; Swann et al., 2017a).

In contrast, clutch state tends to occur suddenly in high-pressure situations, where athletes realize the importance of the performance context (Swann et al., 2017a), and the need to deliver a superior performance to overcome the situation demands. While flow involves a gradual increase of confidence and exploratory context, clutch state requires a rapid elevation of performance to meet critical, immediate targets. This mindset leads to the setting of specific, fixed goals, directly aligned with the immediate demands and the aspired outcomes, providing a clear, focused target for the athletes' efforts. Subsequently, athletes consciously amplify their effort and intensity, channeling their energy towards executing actions with precision. Therefore, the clutch state is characterized by maximal effort and intense concentration (Swann et al., 2017a), rather than the effortless experience characteristic of the flow state. Athletes in the clutch state are fully aware of the demands of the situation and the consequences of success or failure (Swann et al., 2017c). Although skill execution may be automatic, there is heightened awareness and analytical thoughts focused on achieving specific goals (Swann et al., 2017c). The outcomes of the clutch states include optimal performance under pressure and a fulfilling sense of achievement and increased confidence (Boudreau et al., 2022; Schweickle et al., 2021).

Both states share characteristics such as automatic execution of skills, altered perceptions (such as an altered sense of time), deep absorption in the activity and higher confidence (Swann et al., 2017c). These shared characteristics underline the immersive and intense nature of these experiences, but their distinctions lie in the focus of attention, the quality of experience, and the nature of motivation. Flow is marked by harmony and ease, while clutch is defined by intensity and conscious focus on specific goals and outcomes (Swann et al., 2017a).

Newly developed measurement scale for the clutch state, differentiated by its unique characteristics from the flow state, allows for the distinct capture of both psychological states, ensuring discriminant validity between the conceptual domains (Sánchez Vara et al., 2023).

The states of flow and clutch produce distinct and intrinsically rewarding outcomes for athletes. Both are associated with a sense of accomplishment and satisfaction after the experience (Swann et al., 2017a). However, a notable difference lies in the post-experience feeling of each state. After experiencing a flow state, athletes report feeling energized, able to continue or restart the activity without difficulty (Boudreau et al., 2022; Houge Mackenzie et al., 2023; Jackman et al., 2019). In contrast, the clutch state is often followed by a feeling of exhaustion due to the intensity and conscious effort required during these performances (Boudreau et al., 2022; Houge Mackenzie et al., 2023; Swann et al., 2017c).

1.4 Hypothesis development and research model

Research model and hypotheses

The research model (Figure 1) postulates that the level of haptic fidelity of a simulator will affect a user's performance in racing. More precisely, we hypothesize that the effect of the level of haptic fidelity will affect the optimal psychological states, flow and clutch, which in turn affect both perceived and actual performance outcomes.

The potential of haptic simulations lies in their potential to enhance realism, especially in electronic sports training contexts. By investigating how realism influences psychological states in such environments, this study aims to determine the most effective conditions for improving user performance.

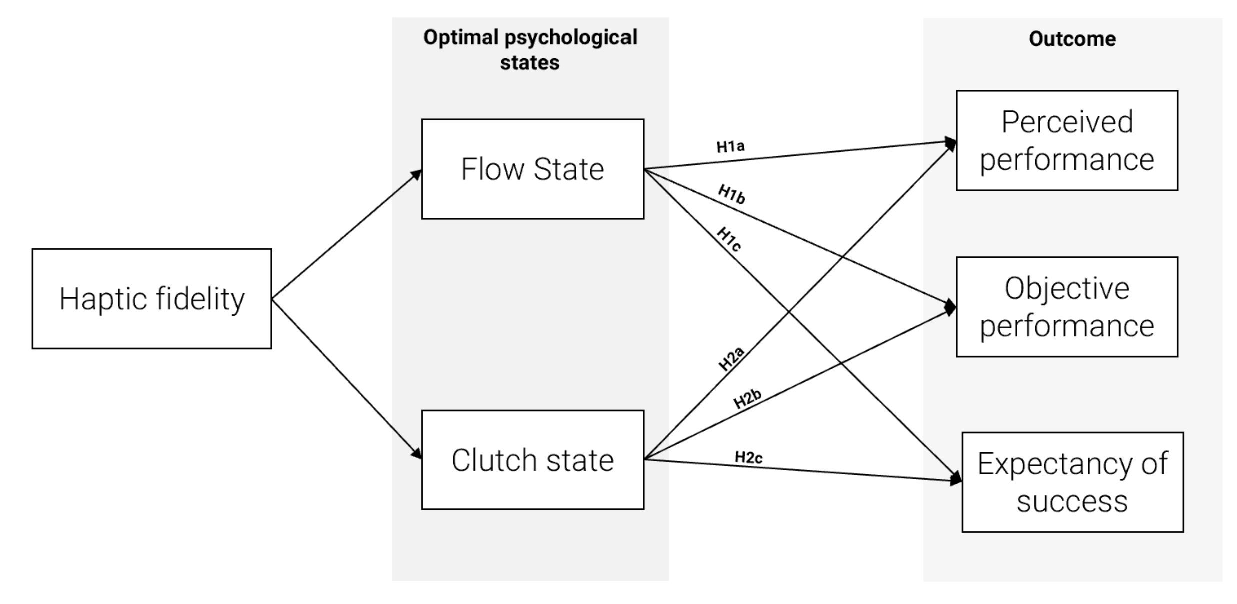

Figure 1: Research model

Haptic fidelity

The use of haptic feedback in virtual environments like simulated racing enhances the immersion, realism and user enjoyment (Daneels et al., 2018; Elson et al., 2014). Haptic fidelity is used as an objective characteristic to describe the quality of a system with haptic feedback. It is used to represent the system's ability to realistically reproduce haptic experiences, and has the potential to increase the perception of realism for the user (Muender et al., 2022). However, haptic fidelity does not describe how a user will experience or perceive the haptic experience, as it only takes into account how the haptics are rendered and which haptic receptors are addressed. It is therefore important to consider the user's perception of realism.

The perception of realism refers to the user's perception of how seamlessly and intuitively the digital items and the physical world are integrated in a virtual environment (Chen and Lin, 2022). Training simulations benefits greatly from a realistic simulator (de Winter et al., 2009; Greenberg and Blommer, 2011), as it can help improve the user's sense of immersion and convince them that they are indeed in a realistic environment, encouraging them to adopt realistic behaviors (Mullen et al., 2011; Slater and Wilbur, 1997).

Haptic fidelity and optimal psychological states

Several factors have been identified as facilitators for inducing flow state, including environmental and situational conditions (Swann et al., 2012), such as quality of feedback (Palomäki et al., 2021), and the realism of the virtual environment (Zumbach et al., 2015). The increased immersion of a technology makes it easier for users to enter a state of flow (Georgiou and Kyza, 2017).

The exploration of clutch state within virtual environments remains an under-researched area, to our knowledge. While no previous studies have directly investigated the occurrence of clutch state in virtual environments, clutch state occurs through a process of receiving feedback about the situation, followed by a decision to increase effort and intensity in the activity (Swann et al., 2017a). The correlation between increased immersion and authentic behaviors (Mullen et al., 2011; Slater and Wilbur, 1997) suggests that clutch states can naturally emerge within well-simulated environments, further emphasizing the importance of realism in virtual settings for inducing both flow and clutch states.

Performance and optimal psychological states

The optimal psychological states, flow and clutch, play a very important part in understanding the performance of an athlete. Previous studies have consistently linked flow to enhanced athletic performance (Harris et al., 2021; Jackman et al., 2021; Swann et al., 2017a), and flow in sports often leads to intrinsic rewards and a perception of superior performance, even if the objective outcome may suggest otherwise (Swann et al., 2022).

The concept of flow is regularly described as underlying superior performance in sports literature (Harris et al., 2021; Jackson and Csikszentmihalyi, 1999; Norsworthy et al., 2017; Swann et al., 2017a). The state of flow contributes significantly to performance enhancement by facilitating the optimal psychological conditions to perform tasks effectively and efficiently (Harris et al., 2021; Jackson and Csikszentmihalyi, 1999; Sklett et al., 2018). The focused concentration characteristic of the flow state could explain improved performance in sport (Harris et al., 2021) and electronic sports (Campbell et al., 2018). This heightened state of engagement enables individuals to perform at their best, often resulting in higher levels of achievement. The intrinsic outcomes of flow, such as enjoyment and emotional engagement (Jackson and Csikszentmihalyi, 1999; Valinatajbahnamiri and Siahtiri, 2021) promote personal fulfillment and skill development.

The literature is suggesting that the realism of virtual environments plays a key role in inducing the flow state, which in turn is intrinsically linked to superior performance. Therefore, we hypothesized that:

H1a: A higher level of haptic fidelity increases the perceived performance through a higher level of experienced flow state

H1b: A higher level of haptic fidelity increases the objective performance through a higher level of experienced flow state

Electronic sports are characterized by the same high levels of performance requirements and pressure inherent in traditional sports (Pluss et al., 2019), requiring athletes to make rapid and precise decision-making under pressure (Himmelstein et al., 2017; Nagorsky and Wiemeyer, 2020). Within electronic sports performance, the emphasis on analytical thinking, dealing with pressure, and decision making (Nagorsky and Wiemeyer, 2020) align with the core characteristics of the clutch state (Swann et al., 2017). The inherent demands of electronic sports could potentially facilitate the occurrence of the clutch state.

Moreover, performing successfully under pressure not only contributes in a more rewarding and enjoyable experience for athletes (Otten, 2007), it has also been suggested that it is the most important factor of success in sports (Mesagno and Mullane-Grant, 2010; Swann et al., 2019, 2016), as clutch performances often have a decisive impact on a competition outcome (Hibbs, 2010).

Clutch state has been associated with superior objective performance outcomes (Schweickle et al., 2021), but also athlete's perception of their own performance (Schweickle et al., 2023). When operationalizing performance outcome in relation to clutch state, it is important to consider the subjective interpretation of the athletes, and not rely only on objective indicators (Schweickle et al., 2023).

Similar to the flow state, increased realism in a virtual environment could potentially facilitate the occurrence of clutch state, which in turn, could lead to superior performance. Therefore, we hypothesized that:

H2a: A higher level of haptic fidelity increases the perceived performance through a higher level of experienced clutch state

H2b: A higher level of haptic fidelity increases the objective performance through a higher level of experienced clutch state

Expectancy of success

In a sporting context, in order to fully grasp the scope of athletic performance, it is essential to take into account not only tangible results, but also the personal interpretation of these results by the athletes themselves (Schweickle et al., 2023). It can happen that athletes, despite a lower objective performance, report a better perception of their performance (Schweickle et al., 2017). The concept of expectancy of success is particularly relevant in this regard, as it highlights the role of positive expectations in reinforcing an athlete's commitment to their performance goals (Wulf and Lewthwaite, 2016). Understanding and exploiting the psychological concepts of performance perception and expectancy of success leads to a more holistic approach to optimizing sports performance.

Expectancy of success, rooted in motivation and self-belief, is an individual's anticipatory judgment about their upcoming performance in a task (Wulf and Lewthwaite, 2016; Xiang et al., 2003). It is a subjective judgment that precedes the act, based on past experiences, self-perception, and contextual cues. Within the sporting literature, enhanced outcome expectancies, in particular self-confidence, have been associated with flow (Harris et al., 2019; Swann et al., 2012). In this sense, performance can be seen as the objective result of a sporting activity, or the perceptual outcome observed post-task execution. While heightened realism and optimal psychological states like flow and clutch might amplify a player's expectancy of success, they don't guarantee superior performance (Schweickle et al., 2023). Therefore, it is important to consider both of these constructs separately.

For a more complete evaluation of an athlete's performance, we will consider the expectancy of success, in addition to the previously mentioned subjective and objective performances. Therefore, we hypothesized that:

H1c: A higher level of haptic fidelity increases the expectancy of success through a higher level of experienced flow state

H2c: A higher level of haptic fidelity increases the expectancy of success through a higher level of experienced clutch state

1.5 Methodology

Experimental design

We carried out a within-subject laboratory experiment to test our hypotheses regarding the relationship between the haptic fidelity and user's performance in car simulators. Our experiment centered on a single factor, namely, the haptic fidelity. This factor was studied across five distinct levels, each corresponding to a different car simulator with haptic feedback. Each of the five simulators displayed varied levels of realism in their haptic systems. These simulators were selected for their diverse haptic feedback technologies, enabling us to examine the variable of interest across a range of realism. Each simulator was characterized by its own level of haptic fidelity, ranging from 1 to 5. Throughout the driving task, driving telemetry was recorded. This telemetry served as a quantitative measure to operationalize drivers' performance. Given the objective to discern the influence the fidelity induced by haptic feedback on performance, using multiple simulators allowed for varied levels of fidelity to be studied concurrently. By examining these variations within subjects, the design facilitated a more comprehensive understanding of the nuances in performance changes attributed to different fidelity levels.

Participants were asked to perform the same task on each car simulator. The sequence in which the simulators were used was randomized to mitigate the influence of learning bias. To ensure an equitable distribution, a Latin square design was implemented, ensuring that each simulator would be tested in each position an equal number of times. Upon completing each task, participants were required to answer a questionnaire for perceptual data.

Throughout the experiment, the participants were wearing a Hexoskin vest, a tool that measures the activity levels. Participants were provided with the appropriate size of Hexoskin wearable vest (ranging from small to triple extra-large) (Carré Technologies Inc., Montréal, Canada) with the standard Hexoskin hip accelerometers secured in the vest pocket, as indicated by the manufacturer.

Haptic Response Index development

The accelerometer measures change in velocity and can capture vibrations experienced by the participant, giving an empirical measure of the haptic output of each simulator. By translating this data into a Power Spectrum Density (PSD), we can gain insights into the frequency and magnitude of vibrations produced. PSD essentially describes how the power of a signal is distributed across different frequency bands. A simulator with a broad and diverse PSD may suggest a richer haptic experience, offering a variety of tactile sensations. In contrast, a simulator with a narrower spectrum might imply limited haptic feedback. The PSD was generated for each simulator and the distribution of vibro-kinetic motion oscillation that creates the haptic experience allowed us to see that each simulator provided different ranges of vibro-kinetic experience that could be attributed to various motions of the vehicle in a race (Figure 2).

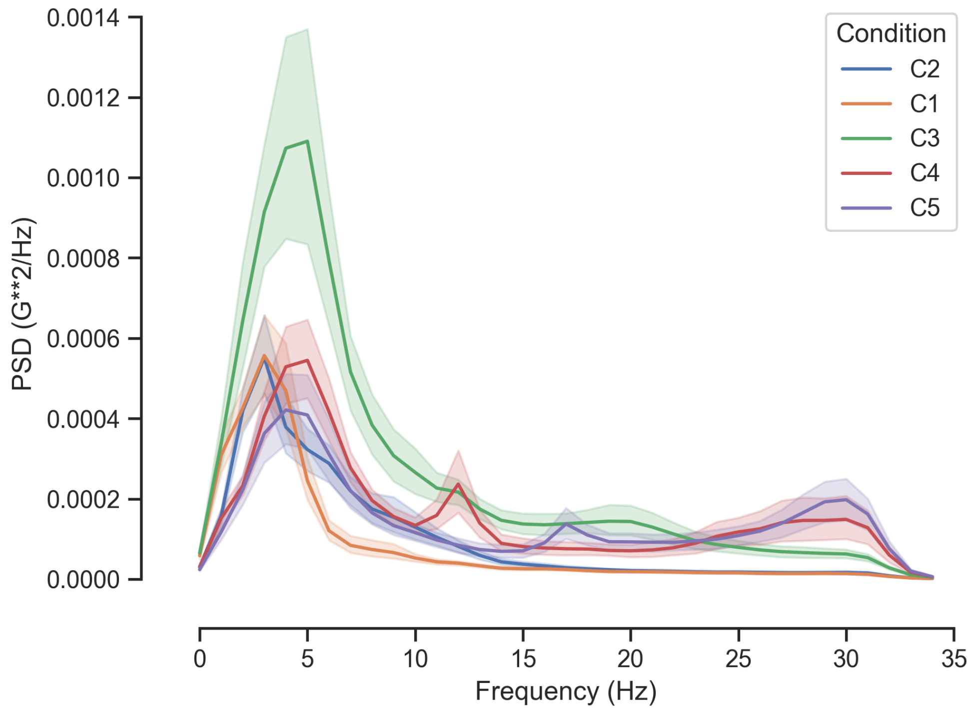

Figure 2: Power spectrum density visualization for each condition

Based on this visualization, we were able to notice three distinctive characteristics of the haptic systems. All simulators peak in low frequency vibrations, which correspond to slower, larger or more prolonged motions, such as gradual accelerations or decelerations or wide turns. These motions are more about the overall movement of the vehicle in the environment. Certain simulators provided medium frequency vibrations, which represent quicker, more defined motions than low frequency associated with intermediate vehicle dynamics. Certain simulators provided high frequency vibrations, which represent subtle motions, such as vibratory feedback from vehicle operations. These vibrations provide the detailed, precise sensations associated with the finer aspects of vehicle motion and interaction with the environment.

Based on these characteristics, we divided the frequencies into three main categories. The division of frequencies represents distinctive characteristics of haptic systems. Low frequency vibrations (1-5 Hz), Medium frequency vibrations (6-20 Hz), and High frequency vibrations (21-34 Hz). Low frequency vibrations represent environmental factors. Medium and high frequency vibrations allow drivers to focus on other elements of the simulated vehicle. This division allowed us to compute the Haptic Response Index (HRI) for each system, which represents the range of vibrations conveyed by the actuators. The higher the ratio, the more varied the vibrations provided by the haptic system. HRI is calculated as:

$$HRI = \frac{PSD_{hf} + PSD_{mf}}{PSD_{lf}}$$

With PSD_{hf} as average high frequency powerband, PSD_{mf} as the average medium frequency powerband, and PSD_{lf} as the average low frequency powerband.

Table 1 presents the HRI for each condition.

Table 1: HRI for each condition

Condition	**Mean (SD)**
C1	0.12 (0.03)
C2	0.23 (0.11)
C3	0.36 (0.25)
C4	0.68 (0.56)
C5	0.69 (0.33)

In order to verify the variability in the perceived level of realism of the five simulators, a manipulation check was conducted. Participants were asked to rate on a scale from 1 (least realistic) to 5 (most realistic) the level of perceived realism of each car simulator.

Statistical analyses showed a significant relationship between the HRI and participants' perception of realism. The HRI was found to have a significant positive effect on the perceived level of realism (β = 0.44, 95% CI[0.26, 0.62], t(114) = 4.83, p<0.001). A higher HRI, indicative of a broader and more varied distribution of power across different frequency bands, was associated with a higher perception of realism, confirming the intended variation in the experimental setup. The variance in haptic feedback across simulators, as quantified by the HRI, influenced the participant's experiences. The perceived realism ratings from participants were not arbitrary but rooted in measurable differences in haptic feedback. This correlation between HRI and perceived realism reinforces the validity of our manipulation, affirming that the participants not only noticed the differences in haptic feedback among simulators, but also associated these differences with varying degrees of realism.

Participants

A total of 25 male individuals participated in this research. The recruitment process for this study emphasized on enlisting participants who possessed a high level of expertise in virtual racing, as the primary focus was on evaluating driving performance. In the field of sport psychology, existing literature has focused on athletes and individuals of high expertise (Jackman et al., 2019). Given this focus in the literature, this study recruited participants with a high level of expertise in Sim Racing. By doing so, it ensures consistency with past research and aligns with the theoretical foundation. The recruitment strategy involved targeting online communities of sim racers via email and social media. The inclusion criteria were: (1) must be over 18 years old, (2) possess a high level of driving experience. Screening of participants was established based on 3 things. The initial solicitation questionnaire asked about the weekly time invested in simulated racing and the number of years of experience. From these answers, only individuals with the highest scores were chosen. Table 3 summarizes the characteristics of our sample. The screening questionnaire also included a question about the familiarity with the circuit. Respondents were prompted to indicate their level of familiarity with well-known race tracks, including Watkins Glen International. Every participant provided written informed consent to take part in this research and received 30$ for their participation as compensation. All participants were informed of their option to withdraw from the study at any point. This study and all its procedures were carried out in accordance with the Research Ethics Board of the institution for which the experiment was conducted (project #: 2023-5396). Some data were lost because of technical issues, but this is handled during the analysis since we are using statistical tests that can handle missing data.

Experimental Task

The task consisted in completing three laps around the virtual race track Watkins Glen International, without any other cars present. Each driving session ended in one of two ways: either after completing three laps, or when six minutes had passed, whichever came first. The main goal was to measure participants' performance under these conditions. Before starting, participants were briefed on the track's layout.

Experimental environment

The experiment was conducted in a large industrial warehouse. The primary reason for this choice was the space requirement; with five car simulators, it was imperative to have a large area to accommodate the setup. Simulators were spaced appropriately to prevent interference from adjacent setups.

Experimental stimuli

Participants were asked to perform the experimental task on five different car simulators. Each car simulator was equipped with the exact same components, the only difference being the haptic feedback of the seat.

The driving task was run using the software iRacing (Chelmsford, United States), a highly realistic simulator widely employed for professional training scenarios. This software is known for providing the most accurate telemetry data. The software was run on a Windows PC (Redmond, United States), and continuously recorded telemetry data, a total of 173 driving behavior metrics, out of which 5 were selected for the subsequent analysis described below.

The circuit chosen for the task was Watkins Glen International, a 5,435 km-long motorsport race track surfaced with asphalt. This selection was motivated by its diverse mix of curves and straight sections, which facilitated a clear distinction between different types of segments (Figure 3). As for the vehicle utilized in the task, the Ferrari 488 GT3 Evo 2020 was selected. To avoid significantly increasing the difficulty of the task, the simulation was set in a partly cloudy environment, in the middle of the afternoon, at 2:48 pm more precisely.

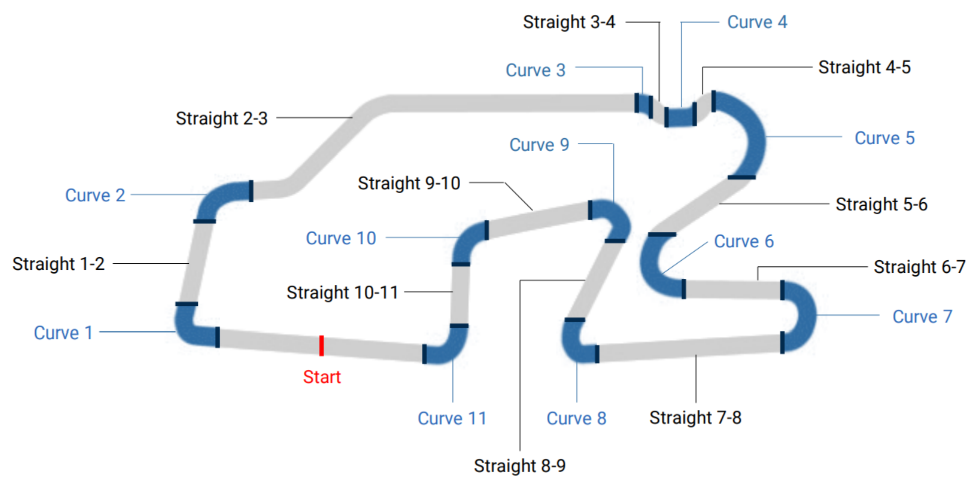

Figure 3: Track breakdown in terms of straight and curved segments

Apparatus

During the whole experiment, participants were seated in an adjustable stationary chair in front of a 49-inch Odyssey G9 DQHD 240Hz HDR1000 QLED Curved gaming monitor (Samsung, Suwon, Corée du Sud). Participants were equipped with a Turn Racing R305 racing wheel with force-feedback steering (Alexandria, United States), mounted on a Ascher Racing B16M-USB button plate (KW Automotive, Fichtenberg, Germany). They were also equipped with Asetek Forte Sim Racing brakes and throttle pedals (Aalborg, Denmark). All simulators were configured with the same hardware, only the haptic systems were different. Before the driving task, participants were asked to adjust the chair to a comfortable distance for driving. Sound was outputted through a Steelseries Arctis Nova 1 gaming headset (Frederiksberg, Denmark) at a volume perceived as comfortable according to each participant (Figure 4).

Figure 4: Driving simulator setup

Experimental procedure

Participants were welcomed to the test environment by the researcher in charge of the study. A detailed presentation of the study was given, and written informed consent was obtained Participants were then invited to put on an appropriately-sized Hexoskin vest (Carré Technologies Inc., Montréal, Canada), before completing an initial questionnaire on a tablet. Once the initial questionnaire was completed, the participant was ready to start the experimental task. For this experiment, participants were asked to complete the racing tasks in an order that was pre-determined for each participant. After the driving task, the experiment ended with a tablet-based questionnaire regarding their perception of realism, perceived level of flow state, clutch state, perceived performance and expectancy of success. Once all five tasks were completed, the participants were allowed to remove the Hexoskin vest. We then proceeded to a short, semi-structured interview to review the experiment on its whole.

Measures

During the experiment, the participants responded to three distinct questionnaires, the first being the aforementioned sollicitation questionnaire. This questionnaire, in addition to the screening inquiries, contained questions for demographic information and propension to cybersickness. The second questionnaire was administered prior to the experiment, including self-efficacy and level of expertise related questions. Following each task, the third questionnaire was administered. Within this questionnaire. participants were asked to assess various aspects of the experience on a perceptual level: perceived level of realism, intensity of flow state, intensity of clutch state, expectancy of success, perceived performance, and cybersickness. To mitigate potential rating bias, all items on the scales were randomized and interchanged. The sequence of the flow scale and clutch scale, as well the expectancy of success scale and performance scale was also randomized. A Hexoskin vest was used to record physiological data, more specifically accelerometer, at a consistent 128 Hz sampling rate.

Table 2 shows the scales and tools used in this study and also presents Cronbach's alpha scores, demonstrating good to excellent reliability for each construct. Details on all items are available in the appendix.

Haptic fidelity

Haptic fidelity refers to the degree to which a virtual or simulated haptic experience replicates the tactile sensations of a real-world counterpart (Muender et al., 2022). The HRI, in this context, becomes a quantifiable metric to measure haptic fidelity.

Perception of realism

The measurement of this construct is based on the Reality Judgment and Presence Questionnaire, designed in order to assess reality and presence judgment within virtual environments (Baños and Perpiña, 2000; Witmer and Singer, 1998). In a previous study, eight items from the Reality Judgment dimension were adapted to measure the perceived level of realism to investigate the level of realism within virtual or augmented reality environments (Chen and Lin, 2022). This adapted scale was relevant to the current study context. Perceived level of realism was assessed using an eight-item scale (five-point Likert scale, 1 = strongly disagree to 5 = strongly agree). The

Cronbach's alpha value for the perceived level of realism was 0.933, which denotes an excellent internal consistency.

Flow and clutch states

The measurement of the flow and clutch states are based on two scales developed as single-factor instruments to capture the core aspects of each psychological state, the Flow State Short Scale (FSSS) and the Clutch State Scale (CSS) (Sánchez Vara et al., 2023). Both scales were developed with the intention of having short-validated scales to study the optimal psychological states, by incorporating the conceptualization of clutch outlined by (Swann et al., 2017b), and the principles of the Integrated Model of Flow and Clutch States which describes the distinctions and similarities between both states (Swann et al., 2019, 2017a).

In order to obtain two distinct measurement scales to independently capture these two states, the authors developed a new measurement scale for the clutch state whose items were based on each characteristic that distinguishes the clutch state from the flow state, in line with the work of Swan et al. 2016. Validated with three separate studies, these two measurement scales capture the essential aspects of each psychological state (Sánchez Vara et al., 2023).

FSSS was used to assess the participants' level of experienced flow state. The FSSS uses a seven-item scale (five-point Likert scale, 1 = strongly disagree to 5 = strongly agree). The Cronbach's alpha value for the perceived level of flow was 0.889, which denotes an excellent internal consistency.

CSS was used to measure the participants' level of experienced clutch state. The CSS uses a five-item scale (five-point Likert scale, 1 = strongly disagree to 5 = strongly agree). The Cronbach's alpha value for the perceived level of clutch was 0.885, which denotes an excellent internal consistency.

Expectancy of success

Expectancy of success refers to an individual's sense of how well they will do on an upcoming task (Xiang et al., 2003). Expectancy of success was assessed using a two-items scale (five-point Likert scale, 1 = strongly disagree to 5 = strongly agree). In the context of this study, expectancy of success was measured after each task, asking how well the participant thought they would perform if they had the opportunity to practice on that simulator. The Cronbach's alpha value for the expectancy of success was 0.959, which denotes an excellent internal consistency.

Perceived performance

Perceived performance was measured using a one-item scale to indicate how participants thought they performed in the previous race (five-point Likert scale, 1 = Very bad to 5 = Very good).

Objective performance

The analysis of car telemetry focused on 5 continuous variables employed to operationalize performance: Lap time, speed, throttle, brake and steering. The fastest lap was selected for each participant as a performance indicator, and the variables were averaged for this lap. A faster lap is associated with a smaller value.

Level of expertise

The level of expertise was measured using a one-item scale (1 = Beginner, 2 = Intermediate, 3 = Advanced, 4 = Expert). The participants were asked to answer based on their evaluation of their own performance.

Self-efficacy

Self-efficacy refers to beliefs in one's capabilities to mobilize the motivation, cognitive resources, and effective strategies to effectively address situational demands (Wood and Bandura, 1989). Self-efficacy was assessed using an eight-items scale (five-point Likert scale, 1 = Strongly disagree, 5 = Strongly agree). The measurement of this concept was based on the New General Self-Efficacy Scale (Chen et al., 2001), a short yet valid tool for capturing the potential benefits of general self-efficacy in various scenarios. The Cronbach's alpha value for the perceived level of clutch was 0.883, which denotes an excellent internal consistency.

Propension to cybersickness and experienced cybersickness

Cybersickness refers to a type of motion sickness that can evoke sensations ranging from discomfort to unease. Discrepancies between perceived sensations and visual display can induce cybersickness (Stanney et al., 1997). Inaccurate haptic feedback from the simulators had the potential to induce cybersickness. Propension to cybersickness was measured with the solicitation questionnaire, as it could potentially influence the perceived level of realism. Although having a low propensity for cybersickness was not a prerequisite to be eligible for the study, it remained a significant factor to consider. During the experiment after each task, cybersickness was measured using a one-item scale (five-point Likert scale, 1 = Not at all, 5 = Extremely). This variable presented a near-zero variance, thus not being usable for our analysis.

Table 2: Study constructs

Construct	Tool/Scale	Source	Cronbach's Alpha
Perception of realism	5-point Likert scale with 8 items ranging from 1 (strongly disagree) to 5 (strongly agree)	Adapted from Chen and Lin (2022)	0.933
Flow state	5-point Likert scale with 7 items ranging from 1 (strongly disagree) to 5 (strongly agree)	Sánchez Vara et al. (2023)	0.889
Clutch state	5-point Likert scale with 5 items ranging from 1 (strongly disagree) to 5 (strongly agree)	Sánchez Vara et al. (2023)	0.885
Expectancy of success	5-point Likert scale with 2 items ranging from 1 (strongly disagree) to 5 (strongly agree)	Adapted from Wigfield and Eccles (2000)	0.959
Perceived performance	5-point Likert scale with 1 item ranging from 1 (very bad) to 5 (very good)	Adapted from Wigfield and Eccles (2000)	n/a
Objective performance	Telemetry data (Lap time, speed, throttle, brake and steering)	n/a	n/a
Level of expertise	One-item scale (1 = Beginner, 2 = Intermediate, 3 = Advanced, 4 = Expert)	n/a	n/a
Self-efficacy	5-point Likert scale with 8 items ranging from 1 (strongly disagree) to 5 (strongly agree)	Adapted from Chen et al. (2001)	0.883
Propension to cybersickness	7-point Likert scale with 6 items ranging from 1 (not at all) to 7 (extremely)	Adapted from Kourtesis et al. (2023)	0.529
Experienced cybersickness	7-point Likert scale with 1 item ranging from 1 (not at all) to 7 (extremely)	Adapted from Kourtesis et al. (2023)	n/a

Data processing

Time-series physiological indices were synchronized with telemetry recordings based on UTC time stamps for the start and end of each race. Processing of physiological data was performed using Cobalt Photobooth (Léger et al., 2019). Data was then prepared, synchronized and analyzed in RStudio using statistical models appropriate for each question or data type.

The systems were operational for the majority of the study, except for one simulator - simulator number 5 - which encountered malfunctions on four occasions. Similarly, condition 3 faced issues on two occasions. In situations where a simulator experienced technical difficulties, the experiment went on by evaluating the other functioning simulators. In total, 119 valid perceptual and physiological data were collected, one per participant per task. The items were computed as an averaged per condition and participant.

Data analysis

We computed a within-subject, repeated measures causal mediation analysis using bootstrapping methods in R with Mediation package (Tingley et al., 2014) to estimate the confidence interval of the indirect effect. To test our hypotheses, we employed a linear mixed-effects model using the "lme4" package in R (Version 4.1.0) (Bates et al., 2015). Given the repeated measures taken from participants after each task, the use of linear mixed-effects model was considered appropriate, since they can handle a nested structure of the data. We included a random intercept for participants. The inclusion of random effects provides a mechanism to capture and account for the variability in the data arising from these groups. Diagnostic plots, including residual plots, suggested no violations of linearity, homoscedasticity, or normality of residuals.

The mediation package allows us to take the regression models just estimated, combine them and estimate the whole mediation. The mediation package calculates the indirect effect of the independent variable on the dependent variable via the mediator using bootstrapping to estimate the confidence intervals for this indirect mediation effect in order to determine if the mediation effect is statistically significant. The complete process of the mediation analysis is available in Appendix 2. Descriptive analyses were used to examine the distributions of demographic characteristics and experience of participants.

1.6 Results

Manipulation check

In order to verify the variability in the perceived level of realism of the five simulators, a manipulation check was conducted. Participants were asked to rate on a scale from 1 (least realistic) to 5 (most realistic) the level of perceived realism of each car simulator.

We fitted a linear mixed model to predict the effect of the HRI on the perceived level of realism. Within this model, the HRI was found to have a significant positive effect on the perceived level of realism (β = 0.44, 95% CI[0.26, 0.62], $t(114) = 4.83$, $p<.001$). A higher HRI, indicative of a broader and more varied distribution of power across different frequency bands, was associated with a higher perception of realism, confirming the intended variation in the experimental setup. The variance in haptic feedback across simulators, as quantified by the HRI, influenced the participant's experiences. The perceived realism ratings from participants were not arbitrary but rooted in measurable differences in haptic feedback. This correlation between HRI and perceived realism reinforces the validity of our manipulation, affirming that the participants not only noticed the differences in haptic feedback among simulators, but also associated these differences with varying degrees of realism.

Descriptive statistics

Table 3 presents the sociodemographic characteristics of participants, all men, included in this study. The included sample of men (n=25) were a mean age of 35 years old (±10.3 years). They had an average of 8.76 years of experience in simulated racing(±6.75 years). They spent an average of 12.64 hours per week playing racing simulation games (±8.83 hours). All participants presented a very low propension to cybersickness, suggesting that the chances of participants to be sick after the experiment are low. These descriptive statistics affirm that our participant pool aligns well with our intended demographic of experienced players in simulated racing, who have a minimal tendency towards cybersickness.

Table 3: Sociodemographic characteristics of participants	
Participant characteristics (n=25)	**Mean (SD)**
Age	35 (10.3)
Years of experience in simulated racing	8.76 (6.75)
Frequency of use (hrs/week) playing simulated racing games	12.64 (8.83)
Self-Assessed driving performance (1=Beginner, 2=Intermediate, 3=Advanced, 4=Expert)	2.72 (0.79)
General Self-efficacy (on a scale of 1 to 5)	4.43 (0.49)
Propension to cybersickness (on a scale of 1 to 5, where 1=Not at all and 5=Extremely)	1.09 (0.15)

Table 4 presents results for single mediation analysis including *a* path, *b* path, direct (*c* path) and bootstrapped indirect effects (*ab* path) for flow and clutch states hypothesized to mediate the relationship between HRI and perceptual performance outcomes (expectancy of success, perceived performance).

Table 4: Results for single mediation analyses on perceptual measures including a path, b path, direct (c path) and bootstrapped indirect effect (ab path).

Hypothesis	**DV**	**a (effect of IV on mediator)**		**b (effect of mediator on DV)**		**c (direct effect)**		**ab (indirect effect)**	
		B (95% CI)	p value	B (95% CI)	p value	B (95% CI)	p value	B (95% CI)	p value
H1a	Perceived performance	**0.19 (0.08, 0.31)**	**<.001**	**0.97 (0.71, 1.24)**	**<.001**	0.02 (-0.17, 0.20)	0.854	**0.19 (0.08, 0.31)**	**<.001**
H1c	Expectancy of success	**0.19 (0.08, 0.31)**	**<.001**	**0.69 (0.46, 0.91)**	**<.001**	0.11 (-0.02, 0.26)	0.105	**0.14 (0.06, 0.23)**	**<.001**
H2a	Perceived performance	**0.23 (0.09, 0.37)**	**0.002**	**0.77 (0.55, 1.00)**	**<.001**	0.04 (-0.14, 0.23)	0.68	**0.18 (0.07, 0.31)**	**<.001**
H2c	Expectancy of success	**0.23 (0.09, 0.37)**	**0.002**	**0.61 (0.44, 0.78)**	**<.001**	0.09 (-0.04, 0.22)	0.188	**0.14 (0.05, 0.24)**	**0.002**

Note: Bootstrap resamples = 1000. CI = confidence interval.

H1a - Mediation of flow on perceived performance

We fitted a linear mixed model to predict the effect of the HRI on the perceived level of flow state. Within this model, the HRI was found to have a significant positive effect on the perceived level of flow state (β = 0.19, 95% CI[0.08, 0.31], t(114) = 3.44, p<.001). Since this effect is statistically significant, it is valid to pursue a mediation analysis, as, for a mediation to take place, the independent variable must significantly impact the mediator.

We fitted a linear mixed model to predict the effect of the perceived level of flow state on the perceived performance, while controlling for the HRI. Within this model, the direct effect of the HRI on the perceived performance is statistically non-significant and positive (β = 0.02, 95% CI[-0.16, 0.20], t(113) = 0.22, p=0.830). The perceived level of flow was found to have a significant positive effect on the perceived performance (β = 0.97, 95% CI[0.71, 1.24], t(113) = 7.25, p<.001). For a mediation to take place, the mediator must explain more or other parts of the variance in the dependent variable than the independent variable. Since the independent variable is no longer significant, we might be in a case of total mediation.

The results of the mediation tests provided a significant positive effect of mediation for H1a. The HRI was shown to have a positive indirect effect on the perceived performance. The effect of the HRI on the perceived performance was fully mediated via the perceived intensity of flow state (β = 0.187, 95% CI[0.081, 0.31], p<.001). Therefore, H1a is supported.

H1c - Mediation of flow on expectancy of success

We fitted a linear mixed model to predict the effect of the perceived level of flow state on the expectancy of success, while controlling for the HRI. Within this model, the direct effect of the HRI on the expectancy of success is statistically non-significant and positive (β = 0.11, 95% CI[-0.02, 0.21], t(113) = 1.63, p=0.105). The perceived level of flow was found to have a significant positive effect on the expectancy of success (β = 0.69, 95% CI[0.46, 0.91], t(113) = 6.08, p<.001). For a mediation to take place, the mediator must explain more or other parts of the variance in the dependent variable than the independent variable. Since the independent variable is no longer significant, we might be in a case of total mediation.

The results of the mediation tests provided a significant positive effect of mediation for H1c. The HRI was shown to have a positive indirect effect on the expectancy of success. The effect of the HRI on the expectancy of success was fully mediated via the perceived intensity of flow state (β = 0.136, 95% CI[0.061, 0.23], $p<.001$). Therefore, H1c is supported.

H2a - Mediation of clutch on perceived performance

We fitted a linear mixed model to predict the effect of the HRI on the perceived level of clutch state. Within this model, the HRI was found to have a significant positive effect on the perceived level of clutch state (β = 0.23, 95% CI[0.09, 0.37], $t(114) = 3.17$, $p=0.002$). Since this effect is statistically significant, it is valid to pursue a mediation analysis, as, for a mediation to take place, the independent variable must significantly impact the mediator.

We fitted a linear mixed model to predict the effect of the perceived level of clutch state on the perceived performance, while controlling for the HRI. Within this model, the direct effect of the HRI on the perceived performance is statistically non-significant and positive (β = 0.04, 95% CI[-0.15, 0.22], $t(113) = 0.38$, $p=0.703$). The perceived level of clutch was found to have a significant positive effect on the perceived performance (β = 0.77, 95% CI[0.55, 1.00], $t(113) = 6.90$, $p<.001$). For a mediation to take place, the mediator must explain more or other parts of the variance in the dependent variable than the independent variable. Since the independent variable is no longer significant, we might be in a case of total mediation.

The results of the mediation tests provided a significant positive effect of mediation for H2a. The HRI was shown to have a positive indirect effect on the perceived performance. The effect of the HRI on the perceived performance was fully mediated via the perceived intensity of clutch state (β = 0.178, 95% CI[0.065, 0.31], $p<.001$). Therefore, H2a is supported.

H2c - Mediation of clutch on expectancy of success

We fitted a linear mixed model to predict the effect of the perceived level of clutch state on the expectancy of success, while controlling for the HRI. Within this model, the direct effect of the HRI on the expectancy of success is statistically non-significant and positive (β = 0.09, 95% CI[-0.04, 0.23], $t(113) = 1.38$, $p=0.171$). The perceived level of clutch was found to have a significant positive effect on the expectancy of success (β = 0.61, 95% CI[0.44, 0.78], $t(113) = 7.14$, $p<.001$).

For a mediation to take place, the mediator must explain more or other parts of the variance in the dependent variable than the independent variable. Since the independent variable is no longer significant, we might be in a case of total mediation.

The results of the mediation tests provided a significant positive effect of mediation for H2c. The HRI was shown to have a positive indirect effect on the expectancy of success. The effect of the HRI on the expectancy of success was fully mediated via the perceived intensity of clutch state (β = 0.142, 95% CI[0.054, 0.24], p=0.002). Therefore, H2c is supported.

H1b - H2b - Mediation analyses on objective performance

Table 4 presents the results of the mediating effect analysis on objective performance, using telemetry variables (Best Lap Time, Throttle, Brake, Speed and Steering Wheel). The data was averaged across two types of segments, curved and straight. The analysis revealed that flow (β = -0.579, 95% CI[-1.11, -0.19], p=0.002) and clutch (β = -0.513, 95% CI[-0.998, -0.13], p=0.004) states fully mediate the relationship between HRI and Best Lap Time. In addition, the results indicated that flow state fully mediates the relationship between HRI and Steering wheel in curved segments (β = -0.01, 95% CI[-0.02, 0.00], p=0.042), speed in straight segments (β = 0.16, 95% CI[0.03, 0.34], p=0.008) and steering wheel in straight segment (β = -0.01, 95% CI[-0.01, 0.00], p=0.064). Also, the results showed that clutch state fully mediates the relationship between HRI and Brake in curved segments (β = -0.12, 95% CI[-0.28, 0.00], p=0.048), steering wheel in curved segments (β = -0.01, 95% CI[-0.03, 0.00], p=0.02), and speed in straight segments (β = 0.12, 95% CI[0.02, 0.26], p=0.012).

Table 5: Results for single mediation analyses on objective performance including a path, b path, direct (c path) and bootstrapped indirect effect (ab path).

Hypothesis	DV	a (effect of IV on mediator)		b (effect of mediator on DV)		c (direct effect)		ab (indirect effect)	
		B (95% CI)	p value	B (95% CI)	p value	B (95% CI)	p value	B (95% CI)	p value
H1b	Best Lap Time	**0.19 (0.08, 0.31)**	**<.001**	**-2.94 (-4.55, -1.33)**	**<.001**	0.32 (-0.76, 1.39)	0.56	**-0.58 (-1.11, -0.19)**	**0.002**
	Throttle (curve)	**0.19 (0.08, 0.31)**	**<.001**	-0.006 (-1.96, 1.95)	0.995	**1.38 (0.18, 2.60)**	**0.022**	0.001 (-0.37, 0.39)	0.978

	Brake (curve)	**0.19 (0.08, 0.31)**	**<.001**	-0.40 (-1.01, 0.21)	0.2	0.19 (-0.24, 0.62)	0.37	-0.077 (-0.23, 0.04)	0.24
	Speed (curve)	**0.19 (0.08, 0.31)**	**<.001**	0.53 (-0.04, 1.11)	0.069	-0.25 (-0.61, 0.13)	0.168	0.10 (-0.01, 0.25)	0.064
	Steering Wheel (curve)	**0.19 (0.08, 0.31)**	**<.001**	**-0.05 (-0.11, -0.001)**	**0.045**	0.01 (-0.03, 0.04)	0.738	**-0.01 (-0.02, 0.00)**	**0.042**
	Throttle (straight)	**0.19 (0.08, 0.31)**	**<.001**	-0.39 (-1.83, 1.06)	0.595	**1.20 (0.33, 2.17)**	**0.008**	-0.07 (-0.4, 0.22)	0.622
	Brake (straight)	**0.19 (0.08, 0.31)**	**<.001**	0.39 (-0.15, 0.94)	0.155	0.33 (-0.02, 0.67)	0.06	0.08 (-0.02, 0.21)	0.148
	Speed (straight)	**0.19 (0.08, 0.31)**	**<.001**	**0.84 (0.21, 1.47)**	**0.009**	-0.05 (-0.48, 0.38)	0.788	**0.16 (0.03, 0.34)**	**0.008**
	Steering Wheel (straight)	**0.19 (0.08, 0.31)**	**<.001**	-0.05 (-0.10, 0.001)	0.056	-0.001 (-0.04, 0.03)	0.964	**-0.01 (-0.02, 0.00)**	**0.064**
H2b	Best Lap Time	**0.23 (0.09, 0.37)**	**0.002**	**-2.22 (-3.56, -0.89)**	**0.001**	0.25 (-0.83, 1.33)	0.65	**-0.51 (-0.998, -0.13)**	**0.004**
	Throttle (curve)	**0.23 (0.09, 0.37)**	**0.002**	0.27 (-1.30, 1.84)	0.731	1.28 (-0.02, 2.53)	0.058	0.06 (-0.30, 0.44)	0.714
	Brake (curve)	**0.23 (0.09, 0.37)**	**0.002**	-0.50 (-1.01, 0.001)	0.051	0.22 (-0.20, 0.65)	0.27	**-0.12 (-0.28, 0.00)**	**0.048**
	Speed (curve)	**0.23 (0.09, 0.37)**	**0.002**	0.26 (-0.21, 0.74)	0.271	-0.22 (-0.59, 0.16)	0.27	0.06 (-0.05, 0.19)	0.27
	Steering Wheel (curve)	**0.23 (0.09, 0.37)**	**0.002**	**-0.06 (-0.10, -0.02)**	**0.008**	0.01 (-0.03, 0.04)	0.64	**-0.01 (-0.03, 0.00)**	**0.02**
	Throttle (straight)	**0.23 (0.09, 0.37)**	**0.002**	-0.38 (-1.54, 0.77)	0.51	**1.23 (0.37, 2.09)**	**0.01**	-0.07 (-0.34, 0.16)	0.562
	Brake (straight)	**0.23 (0.09, 0.37)**	**0.002**	0.34 (-0.09, 0.78)	0.118	0.32 (-0.02, 0.65)	0.06	0.07 (-0.02, 0.18)	0.114
	Speed (straight)	**0.23 (0.09, 0.37)**	**0.002**	**0.63 (0.11, 1.14)**	**0.017**	-0.03 (-0.44, 0.41)	0.862	**0.12 (0.02, 0.26)**	**0.012**
	Steering Wheel (straight)	**0.23 (0.09, 0.37)**	**0.002**	-0.02 (-0.07, 0.02)	0.251	-0.004 (-0.4, 0.03)	0.79	-0.004 (-0.01, 0.00)	0.24

Note: Bootstrap resamples = 1000. CI = confidence interval.

Table 6 below presents an overview of the hypotheses that were supported and not supported.

Table 6: Summary of conclusions		
Hypothesis	**Description**	**Conclusion**
H1a	A higher level of haptic fidelity increases the **perceived performance** through a higher level of experienced **flow state**	Supported
H1b	A higher level of haptic fidelity increases the **objective performance** through a higher level of experienced **flow state**	Partially Supported
H1c	A higher level of haptic fidelity increases the **expectancy of success** through a higher level of experienced **flow state**	Supported
H2a	A higher level of haptic fidelity increases the **perceived performance** through a higher level of experienced **clutch state**	Supported
H2b	A higher level of haptic fidelity increases the **objective performance** through a higher level of experienced **clutch state**	Not supported
H2c	A higher level of haptic fidelity increases the **expectancy of success** through a higher level of experienced **clutch state**	Supported

1.7 Discussion

A better understanding of how haptic feedback influences cognitives states and performance in a virtual environment is essential for advancing interactive technology design. The goal of this study was to identify and analyze the effect of the haptic fidelity of a system, characterized by the range and variety of vibrations, on perceived flow and clutch states, and how these states, in turn, affect the outcome. This study focused on understanding how enhanced haptic feedback, as measured by the HRI, influences users' experiences of flow and clutch states, and how these states mediate performance outcomes in simulated racing environments.

Findings

The results from our empirical analyses confirm our hypotheses, demonstrating a significant relationship between haptic fidelity and performance outcomes, fully mediated by flow and clutch states. The results reveal that enhanced haptic feedback, through its diverse vibrational range, significantly elevates the psychological states of flow and clutch, which in turn positively influence users' perceptions of their performance and expectancy of success. These findings indicate a complex yet coherent interaction between technological input and psychological output, highlighting the important role of haptic fidelity in simulated training environments.

Theoretical contributions

This study has several theoretical contributions. We were able to identify 3 contributions. Firstly, by investigating the mechanisms underlying optimal performance in racing simulation context, results provide a comprehensive understanding of the relationship between haptic fidelity, clutch state and performance outcomes, which was missing in the literature, to our knowledge. This study contributes to the quantitative exploration of clutch state in electronic sports, a concept previously mainly studied within traditional sports contexts through qualitative methods (Swann et al., 2017a). This study used a recently developed scale (Sánchez Vara et al., 2023) to capture the occurrence of clutch state, being one of the first studies to research the clutch state from a quantitative perspective. Our findings on the significant mediating effect of the clutch state on the performance align with the literature, suggesting that the clutch state is reported to underlie performance (Swann et al., 2019, 2016). Furthermore, this study was able to extend its knowledge into virtual settings, whereas previously, the clutch state was mainly, to our knowledge, studied in traditional sports contexts.

Secondly, the relationship between flow and performance has been studied in sports and gaming contexts for many years. Aligning with previous studies, our results confirm the reliable relationship between flow state and performance in sport and gaming (Harris et al., 2021; Jackman et al., 2021; Swann et al., 2017a). Although, in previous systematic reviews, it has been suggested that a proportion of the performance variance could not be attributed to the flow state (Harris et al., 2021). With this study, we aimed to get a better understanding of the mechanisms underlying superior performance. Our results showed that the perceived performance could also be explained by the clutch state, since both flow state and clutch state fully mediates the relationship between haptic fidelity and perceived performance. These results are in line with the literature, stating that both states lead to perceived superior performance (Swann et al., 2022), and measuring only flow can only lead to a partial understanding of the mechanisms underlying performance. Flow state has been studied in the literature for a longer time, and we have gained a good understanding of its implications in a sports context. However, the clutch state is a rather new concept, which lacks a bit of scientific experiment to explain its dimensions and implication, even though it has gained a noteworthy increasing interest from researchers (Schweickle et al., 2021). By also considering the clutch state, our study offers a more comprehensive view of the mechanisms underlying performance, and further acknowledges the importance of the clutch state when measuring performance outcomes in high-stakes settings.

Thirdly, numerous studies have employed flow theory to investigate user experience in immersive technology research, suggesting that immersive technology enables users to immerse themselves in a flow state (Georgiou and Kyza, 2017). However, many studies often focus predominantly on users' psychological state as a cognitive response to the immersive technology, frequently overlooking the antecedents and consequences of using such technology (Suh and Prophet, 2018). Flow experience has previously been suggested to be influenced by task-related factors, such as quality of feedback (Palomäki et al., 2021), realism of the virtual environment (Zumbach et al., 2015) and environmental and situational conditions (Swann et al., 2012). This study bridges the gap between technology and psychology by demonstrating how technological enhancements, specifically through high-fidelity haptic feedback, can significantly influence psychological experiences. This research aimed to understand specifically this aspect, by measuring the influence of the fidelity of the haptic feedback on the flow and clutch state. Our results suggest that the relationship between the haptic fidelity and performance is entirely mediated by flow and clutch state. This implies that the quality and richness of haptic feedback could indirectly influence participants' perception of their performances, through the psychological mechanism of the flow and clutch state. The non-significant direct effect of the haptic fidelity on performance outcomes highlights the complexity of this relation. With a mediation analysis, we were able to further understand the mechanism underlying optimal performance, since the subjective perception of performance in simulated environments is influenced by the psychological states induced by the technology.

Practical implications

The findings of this study have substantial practical implications for designers of haptic systems, particularly in racing simulation contexts. The introduction of the HRI as a quantitative measure of haptic fidelity represents a significant advancement, offering designers a tangible metric to optimize the user experience. Our findings suggest that higher HRI scores, indicative of more varied and rich haptic feedback, enhance the perception of realism. This is particularly relevant in racing simulation since a heightened sense of realism can heavily contribute to immersion (Daneels et al., 2018; Elson et al., 2014). Moreover, the study demonstrates that richer haptic feedback positively influences players' expectancy of success; players could predict that, with practice, they would be able to perform better when using richer haptic systems. Therefore, when designing haptic systems, it is important for designers to prioritize high-fidelity haptic feedback. This insight is invaluable for the development of user-centric haptic systems that meet with users' performance expectations and enhance their overall interaction with the virtual environment.

Limitations and future research

A notable limitation of this study is the exclusive inclusion of male participants. Despite concerted efforts during the solicitation process to recruit a gender-diverse participant group, unfortunately, no female participants responded positively to our invitation. While the findings provide valuable insights into the relationship between haptic fidelity and performance outcomes in a simulated racing environment, the generalizability of these results may be limited due to the lack of gender diversity in the participant pool. Research in psychology and performance studies indicates that there can be differences in how males and females perceive and respond to technological interfaces and psychological states (Chalabaev et al., 2013). The absence of female participants in this study means that the results may not fully capture these potential gender-specific variations in the experience of haptic fidelity and the resultant psychological states. Therefore, while the findings are relevant and informative for the male population in racing simulation contexts, caution should be exercised in extending these conclusions to a broader, more diverse population. Future research should aim to include a more gender-diverse participant group to explore whether the observed relationships hold consistently across genders. Such inclusive research would enhance the understanding of these dynamics in a more representative sample, thereby providing a more holistic view of the role of technology in performance psychology.

A significant limitation of our study applies to the frequency range capabilities of the accelerometer used. This accelerometer was designed to capture vibration up to a maximum of 35 Hz. However, the actuators of the car simulators are sometimes capable of producing up to 100 Hz vibrations. This discrepancy in the frequency range potentially restricted our ability to fully capture and analyze the complete spectrum of haptic feedback experienced by participants. While the accelerometer's frequency range did not capture the full extent of the haptic feedback, it still provided a reliable and accurate measure within its operational range. This range was considered sufficient to achieve the primary objectives of our study. The Hexoskin vest provided a practical and non-intrusive way to measure haptic feedback while participants were engaged in the simulation. Future research should consider using accelerometers with a broader frequency range that aligns more closely with the full capabilities of the simulators. This would allow a more comprehensive capture of the haptic feedback.

Finally, with our experiment, while this study successfully captured the occurrence and intensity of flow and clutch states, it did not distinguish between these states within a single racing event. Flow and clutch states are distinct psychological states, and their processes of occurrence are influenced by distinctly different factors (Swann et al., 2017a). It has been suggested that both states cannot be experienced at the same time, although participants can report that both states can be experienced during the same activity with transitions from one state to the other (Swann et al., 2019). Flow is often described as a state of immersive engagement that develops over time, whereas the clutch state is typically triggered in response to high-pressure situations (Swann et al., 2019), particularly towards critical moments of an event where the outcome is significantly impacted by the athlete's focused effort and intensity (Jackman et al. 2020; Swann et al., 2017a). This conceptual differentiation highlights the complexity of athletes' psychological experiences, suggesting that these states are likely to occur independently and influenced by distinct situational conditions within the same sporting activity. Our research aimed to capture the occurrence of both states, but the methodology, which involved measurement after each task, inherently captured both states simultaneously. This approach does not allow us to distinguish the specific moment of occurrence or the unique antecedents of these two distinct psychological states, nor does it allow us to conclude anything about these two states overlapping. Future research should aim to separate these states within the same context, providing a clearer understanding of their distinct antecedents and impacts on performance outcome. By refining the measurement approach to differentiate the timing and antecedents of flow and clutch states, future studies could provide deeper insights into how these states contribute to performance.

1.8 Conclusion

The present study investigated the mechanisms underlying superior performance in a simulated racing context, by researching the mediating influence of flow and clutch states on the relationship between haptic fidelity and performance outcomes. Haptic fidelity was found to have a significant and positive effect on performance outcomes, with this relationship being fully mediated through the experienced flow and clutch states.

The main theoretical implications of this research is that it advances our understanding of the clutch state in simulated environments, traditionally a concept explored within physical sports contexts through qualitative methodologies. By using a quantitative approach, this research is among the first in exploring clutch state within electronic sports to our knowledge, offering new insights into the mechanism of performance within simulated high-stakes scenarios. Additionally, it offers a more comprehensive understanding of the influence of psychological state on performance outcome by taking into account both clutch and flow state.

In terms of practical implications, this study has significant repercussions for the design and development of haptic systems. The introduction of the HRI as a tool for measuring haptic fidelity provides a notable advancement in the field, providing a quantitative measure to assess the impact of haptic feedback on user experience. Our results highlight the importance of high-fidelity haptic feedback, not just for enhancing the realism of a simulation, but also for increasing users' optimal psychological states. These findings are invaluable for designers and developers, offering guidance on optimizing haptic systems to enhance user interaction and performance in virtual environments.

1.9 Appendix

Appendix 1. Questionnaire items

In the translation of questionnaires from English to French, we employed a rigorous multi-step process to ensure the integrity and validity of the study (Tsang et al., 2017). Initially, the questionnaires were translated into French, with the expertise of bilingual individuals. This was followed by a back-translation step, where an independent translator, unaware of the original questionnaire translated the French version back into English, to identify and correct any discrepancies or losses in meaning. Next, a pretest was conducted with a small sample of native French speakers who provided feedback on clarity and any ambiguous translated items.

Construct	Items	Translation	Source
Perceived realism	To what extent did the experience seem real to you?	Dans quelle mesure l'expérience vous a-t-elle semblé réelle?	Chen and Lin (2022)
	In your opinion, how was the quality of the images in the virtual world?	Selon vous, quelle était la qualité des images dans la simulation?	
	To what extent was what you saw in the virtual world similar to reality?	Dans quelle mesure ce que vous avez vu dans la simulation était-il similaire à la réalité?	
	How real did the virtual objects seem to you?	Dans quelle mesure les objets virtuels vous ont-ils semblé réels?	
	To what extent was what you experienced in the virtual world congruent to other experiences in the real world?	Dans quelle mesure ce que vous avez vécu dans le simulateur correspond-il à d'autres expériences dans le monde réel ?	
	To what extent did you feel you "went into" the virtual world?	Dans quelle mesure avez-vous eu l'impression d'avoir intégré le monde virtuel?	
	To what extent did your interactions with the virtual world seem natural to you, like those in the real world?	Dans quelle mesure vos interactions avec la simulation vous ont-elles semblé naturelles, comme celles du monde réel?	
	To what extent did you feel you "were" physically in the virtual world?	Dans quelle mesure avez-vous eu l'impression d'être physiquement dans la simulation?	
Expectancy of success	Compared to other students, how well do you expect to do in math this year?	Dans quelle mesure pensez-vous obtenir une bonne performance lors des prochaines courses?	Adapted from Wigfield and Eccles (2000)
	How well do you think you will do in your math course this year?	Quel serait votre niveau de performance dans les prochaines courses?	
Performance	How have you been doing in math this year?	Comment avez-vous performé dans la course que vous venez d'accomplir?	

Flow	I felt I was competent enough to meet the high demands of the situation	Je me suis senti suffisamment compétent pour répondre aux exigences élevées de la situation.	Sánchez Vara et al. (2023)
	I had a strong sense of what I must do and what I wanted to achieve	J'avais une idée précise de ce que je devais faire et de ce que je voulais accomplir	
	It was really clear to me that I was doing well	Il était clair pour moi que je m'en sortais bien	
	I was completely focused on the task at hand	J'étais complètement concentré sur la tâche à accomplir	
	I felt in total control of my mind and body	Je me sentais en plein contrôle de mon corps et de mon esprit.	
	I was not worried about what others may have been thinking of me	Je ne me souciais pas de ce que les autres pouvaient penser de moi	
	I loved the feeling of that performance and want to capture it again	J'ai aimé la sensation de cette performance et je veux la retrouver.	
Clutch	I was fully concentrated; I couldn't have concentrated more; I was completely committed to what I need to do	J'étais totalement concentré; je n'aurais pas pu l'être davantage; j'étais totalement engagé dans ce que je devais faire	Sánchez Vara et al. (2023)
	I was playing better because I was pushing to my limit consciously, giving my maximum	Je conduisais mieux parce que je repoussais consciemment mes limites, en donnant mon maximum	
	Being more aware of my context and its relevance, I was thinking very clearly about me and what I was doing	Plus conscient de mon contexte et de sa pertinence, je pensais très clairement à moi et à ce que je faisais	
	There was a full activation, with a mix of nerves and excitement, that pumped up my energy	Il y a eu une activation complète, avec un mélange de nervosité et d'excitation, qui m'a donné de l'énergie	
	There's no worrying about anything else, I was just focusing on the next move	Je ne me préoccupe de rien d'autre, je me concentrais seulement sur le prochain mouvement	
Self-efficacy	I will be able to achieve most of the goals that I have set for myself.	Je suis en mesure d'atteindre la plupart des objectifs que je me fixe.	Chen et al. (2001)
	When facing difficult tasks, I am certain that I will accomplish them.	Lorsque je suis confronté à des tâches difficiles, je suis certain de les accomplir.	
	In general, I think that I can obtain outcomes that are important to me.	En général, je pense que je peux obtenir des résultats qui sont importants pour moi.	
	I believe I can succeed at most any endeavor to which I set my mind.	Je crois que je peux réussir dans tout ce que j'entreprends.	
	I will be able to successfully overcome many challenges.	Je suis capable de relever avec succès de nombreux défis.	

	I am confident that I can perform effectively on many different tasks.	J'ai confiance en ma capacité à accomplir efficacement de nombreuses tâches différentes.	
	Compared to other people, I can do most tasks very well.	En comparaison à d'autres personnes, je peux très bien accomplir la plupart des tâches.	
	Even when things are tough, I can perform quite well.	Même dans les moments difficiles, j'arrive à bien performer.	
Propension to cybersickness	Do you experience nausea (e.g., stomach pain, acid reflux, or tension to vomit)? Do you experience dizziness ? Do you experience disorientation ? Do you experience postural instability? Do you experience visually induced fatigue? Do you experience visually induced discomfort?	Pendant ou suite à une expérience de simulation, veuillez indiquer si vous avez déjà ressenti les symptômes suivants: - Nausée (maux d'estomac, envie de vomir) - Étourdissement - Désorientation - Perte d'équilibre - Fatigue - Inconfort visuel (vision floue)	Adapted from Kourtesis et al. (2023)
Experienced cybersickness		Avez-vous ressenti des malaises durant l'utilisation de ce simulateur? (nausée, étourdissement, désorientation, perte d'équilibre, fatigue, inconfort visuel, etc.)	Adapted from Kourtesis et al. (2023)

Appendix 2. Mediation analysis procedure

With a mediation analysis, we seek to understand the mechanism by which an independent variable influences a dependent variable through a mediator variable, in this case, flow and clutch. To test whether the independent variable affects the dependent variable through a mediator, the analysis estimates and tests two regression models: one linking the independent variable to the mediator, and another linking both the independent variable and mediator to the dependent variable. They both need to be simultaneously significant for an indirect effect to be claimed (Judd et al., 2001; Montoya and Hayes, 2017).

The first step is to test the total effect, which determines whether the independent variable has any influence on the dependent variable. Opinions differ on the necessity of this relationship's significance for mediation. One perspective argues that a significant relationship is needed, otherwise, we cannot assert that changes in the independent variable influence the dependent variable, even if there's a significant indirect effect. However, this school of thought is gradually losing favor to another perspective, which posits that a significant direct relationship between the independent and dependent variables is not essential for a mediation to occur. Similar to how correlation does not prove causation, the absence of correlation does not disprove causation (Andrew F. Hayes, 2018, p.80). Mediation analysis as practiced now no longer imposes evidence of simple association between the independent variable and the dependent variable as a precondition. Therefore, a significant total effect is not mandatory to pursue a mediation analysis.

To establish any mediation, the independent variable must significantly affect the mediator. We then do another simple linear regression of the independent variable onto the mediator, plus any covariates we might have.

Then, we confirm that the mediator affects the dependent variable while controlling for the independent variable. This means that for a meditation to take place, the mediator must explain more or other parts of the variance in the dependent variable than the independent variable. We do a simple linear regression of the independent variable and the mediator onto the dependent variable plus any covariates we might have.

As an output, if the mediator has a significant effect on the dependent variable, we can already say that there is a mediation. Also, if the independent variable is no longer significant within this regression model, we are in a case of complete mediation, which means that the total effect of the independent variable on the dependent variable is explained by the mediator. If the independent variable were still significant, we would be in a case of partial mediation, which means that there is another effect of the independent variable on the dependent variable that doesn't go through the mediator.

To estimate the entire model, we use the mediation package, which takes the regression models we just estimated, combines them and estimates the whole mediation.

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Chapitre 4: Conclusion

Le principal objectif de ce mémoire était d'évaluer dans quelle mesure l'utilisation de la technologie haptique visant à augmenter le niveau de réalisme d'une simulation influence les résultats de performance des utilisateurs en situation de simulation de course.

L'objectif de ce mémoire par article était de mieux comprendre les états psychologiques sous-jacents à la performance sportive de haut niveau. Tout d'abord, le deuxième chapitre de ce mémoire décortique les états mentaux des athlètes pendant des performances sportives, sous la forme d'une revue de littérature. Cette revue de littérature révèle l'importance de l'état de *flow* et l'état décisif dans la compréhension de la performance sportive. Ensuite, dans le troisième chapitre, ce mémoire rapporte les résultats d'une expérience en laboratoire.

Rappel des questions de recherche et principaux résultats

L'étude a examiné les mécanismes qui sous-tendent la performance optimale dans un contexte de simulation de course, en évaluant les effets de médiation de l'état de *flow* et de l'état décisif (*clutch state)*. Les résultats des analyses de ce mémoire ont permis de répondre à la question de recherche suivante:

Dans quelle mesure l'utilisation de la technologie haptique visant à augmenter le niveau de réalisme d'une simulation influence les résultats des utilisateurs dans une situation de simulation de course à travers l'état de flow et l'état décisif?

Cette question de recherche a pu être déclinée en plusieurs hypothèses, basées sur la littérature scientifique dans le domaine, entre autres, de la psychologie du sport, de l'interaction humain-interface et de sports électroniques:

H1a: Un plus haut niveau de fidélité haptique augmente la perception de performance, à travers un plus haut niveau d'état de *flow* perçu.

H1b: Un plus haut niveau de fidélité haptique augmente la performance objective, à travers un plus haut niveau d'état de *flow* perçu.

H1c: Un plus haut niveau de fidélité haptique augmente l'espérance de succès à travers un plus haut niveau d'état de *flow* perçu.

H2a: Un plus haut niveau de fidélité haptique augmente la perception de performance, à travers un plus haut niveau d'état décisif perçu.

H3b: Un plus haut niveau de fidélité haptique augmente la performance objective, à travers un plus haut niveau d'état décisif perçu.

H2c: Un plus haut niveau de fidélité haptique augmente l'espérance de succès à travers un plus haut niveau d'état décisif perçu.

Afin de tester ces hypothèses, une étude en laboratoire a été effectuée auprès de 25 participants experts qui ont complété 3 tours de circuit sur 5 simulateurs de course différents, tous équipés d'un système de retour haptique.

Les résultats de cette expérience ont permis de démontrer que la fidélité haptique a un effet positif significatif sur la performance perçue ainsi que sur l'espérance de succès, et que cette relation est médiée par l'état de *flow* et l'état décisif. Ces résultats soulignent la complexité entre les outils technologiques et l'expérience utilisateur, révélant le rôle important du réalisme du retour haptique dans l'amélioration de l'expérience vécue par l'utilisateur dans les environnements simulés.

Contributions de l'étude

Les principales implications théoriques de cette recherche sont qu'elle fait progresser notre compréhension de l'état décisif dans des environnements simulés, un concept traditionnellement exploré dans des contextes de sports physiques par le biais de méthodologies qualitatives. En utilisant une approche quantitative, cette recherche est l'une des premières à explorer l'état décisif dans les sports électroniques, offrant de nouvelles perspectives sur le mécanisme de la performance dans des scénarios simulés à enjeux élevés. En outre, elle offre une compréhension plus complète de l'influence de l'état psychologique sur les résultats de performance en tenant compte à la fois de l'état décisif et de l'état de *flow.* En démontrant la médiation complète de la fidélité haptique sur la performance perçue à travers l'état de *flow* et l'état décisif, cette recherche offre de nouvelles perspectives sur les mécanismes sous-jacents à une performance supérieure dans des environnements virtuels. Cette relation de médiation complète montre l'importance de considérer, dans un contexte de performance sportive, autant l'état décisif que l'état de *flow*, ce concept déjà vastement étudié dans la littérature scientifique. Aussi, à notre connaissance, peu d'études s'étaient intéressées à la relation entre les technologies de simulation et les états psychologiques optimaux dans un contexte aussi spécifique que les sports électroniques, et cette étude permet ainsi de combler ce manque dans la littérature.

En termes d'implications pratiques, cette étude a des répercussions significatives sur la conception et le développement de systèmes haptiques. L'introduction du *Haptic Response Index (HRI)* en tant qu'outil de mesure de la fidélité haptique constitue une avancée notable dans ce domaine, en fournissant une mesure quantitative pour évaluer l'impact du retour haptique sur l'expérience de l'utilisateur. Nos résultats soulignent l'importance d'un retour haptique de haute fidélité, non seulement pour améliorer le réalisme d'une simulation, mais aussi pour accroître les états psychologiques optimaux des utilisateurs. Ces résultats sont inestimables pour les concepteurs et les développeurs, car ils offrent des conseils sur l'optimisation des systèmes haptiques afin d'améliorer l'interaction et les performances des utilisateurs dans les environnements virtuels.

Limites et pistes de recherches futures

Une limite notable de cette étude est l'inclusion exclusive de participants masculins. Bien que les résultats fournissent des indications précieuses sur la relation entre la fidélité haptique et la performance dans un environnement de simulation de course, la généralisation de ces résultats peut être limitée en raison du manque de diversité des sexes dans le groupe de participants. Les recherches futures devraient viser à inclure un groupe de participants plus diversifié sur le plan du genre afin d'explorer si les relations observées se maintiennent de manière cohérente entre les genres.

Ensuite, une autre limite concerne la gamme de fréquences de l'accéléromètre utilisé. Cet accéléromètre a été conçu pour capter des vibrations jusqu'à un maximum de 35 Hz. Or, les actuateurs des simulateurs de voiture sont parfois capables de produire des vibrations allant jusqu'à 100 Hz. Cet écart a potentiellement limité notre capacité à capturer et à analyser le spectre complet du retour haptique ressenti par les participants. Toutefois, l'accéléromètre nous a tout de même fourni une mesure fiable et précise dans sa gamme opérationnelle. Cette plage a été jugée suffisante pour atteindre les principaux objectifs de notre étude. Les recherches futures devraient envisager l'utilisation d'accéléromètre avec une gamme de fréquences plus large qui s'aligne plus étroitement sur les capacités complètes des simulateurs, pour avoir une évaluation plus complète du retour haptique.

Finalement, bien que notre étude ait réussi à capturer l'occurrence et l'intensité de l'état de *flow* et de l'état décisif, elle n'a pas fait la distinction entre ces états au cours d'un seul événement de course. Les recherches futures devraient viser à séparer ces états dans un même contexte, pour mieux comprendre leurs antécédents distincts et leurs impacts sur la performance.

Pour conclure, ce mémoire montre de quelle manière la technologie haptique peut avoir un impact sur la performance de conduite dans un contexte de sports électroniques. Avec ce travail de recherche, nous sommes parvenus à exploiter un concept relativement nouveau dans la littérature sportive, l'état décisif, et nous avons été en mesure d'explorer ce concept dans un contexte de sports électroniques, marquant les bases des travaux de recherches futures qui s'intéresserait à la psychologie du sport électronique. En mettant en évidence l'impact significatif de la fidélité haptique sur les états psychologiques et la performance de l'utilisateur dans des environnements simulés, nous ouvrons la voie à de futures recherches qui permettront d'affiner et d'élargir ces connaissances. Ces futures recherches permettront d'affiner et d'élargir ces connaissances, et d'approfondir la littérature sur l'état décisif, afin de contribuer davantage au développement des pratiques sportives.

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