UNIVERSIDADE ESTADUAL PAULISTA
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Gisele Chiozi Gotardi

VISUALLY GUIDED ACTIONS OF URBAN TRAFFIC USERS: TOWARDS AN AFFORDANCE-BASED APPROACH

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Tese apresentada como requisito à obtenção do título de Doutor à Universidade Estadual Paulista "Júlio de Mesquita Filho" - Programa de Pós-Graduação em Ciências da Motricidade, área de concentração 21, sob a orientação do Prof. Dr. Sérgio Tosi Rodrigues e do Prof. Dr. John van der Kamp, e co-orientação da Profa. Dra. Martina Navarro.

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VRIJE UNIVERSITEIT

VISUALLY GUIDED ACTIONS OF URBAN TRAFFIC USERS

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door

Gisele Chiozi Gotardi

geboren te Botucatu, Brazilië

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ATA DA DEFESA PÚBLICA DA TESE DE DOUTORADO DE GISELE CHIOZI GOTARDI, DISCENTE DO PROGRAMA DE PÓS-GRADUAÇÃO EM CIÊNCIAS DA MOTRICIDADE, DA FACULDADE DE CIÊNCIAS - CÂMPUS DE BAURU.

Aos 27 dias do mês de agosto do ano de 2024, às 09:00 horas, por meio de Videoconferência, realizou-se a defesa de TESE DE DOUTORADO de GISELE CHIOZI GOTARDI, intitulada **VISUALLY GUIDED ACTIONS OF URBAN TRAFFIC USERS: TOWARDS AN AFFORDANCE-BASED APPROACH**. A Comissão Examinadora foi constituida pelos seguintes membros: Prof. Dr. SERGIO TOSI RODRIGUES (Orientador(a) - Participação Virtual) do(a) Departamento de Educação Física / Faculdade de Ciências - Unesp Bauru, Prof. Dr. FABIO AUGUSTO BARBIERI (Participação Virtual) do(a) Departamento de Educação Física / Faculdade de Ciências - Unesp Bauru, Prof. Dr. RENATO DE MORAES (Participação Virtual) do(a) Programa de Pós-graduação em Educação Física e Esporte / Universidade de São Paulo - Escola de Educação Física e Esportes de Ribeirão Preto - SP, Prof. Dr. JOSE ANGELO BARELA (Participação Virtual) do(a) Departamento de Educação Física / Instituto de Biociências - Unesp Rio Claro, Profa. Dra. DANIELA GODOI JACOMASSI (Participação Virtual) do(a) Departamento de Educação Física e Motricidade Humana / Universidade Federal de São Carlos. Após a exposição pela doutoranda e arguição pelos membros da Comissão Examinadora que participaram do ato, de forma presencial e/ou virtual, a discente recebeu o conceito final APROVADA. Nada mais havendo, foi lavrada a presente ata, que após lida e aprovada, foi assinada pelo(a) Presidente(a) da Comissão Examinadora.



Prof. Dr. SERGIO TOSI RODRIGUES

‘The real cycle you're working in is a cycle called yourself. The machine that appears to be "out there" and the person that appears to be "in here" are not two separate things. They grow toward Quality or fall away from Quality together.'

Robert M. Pirsig (Zen and the Art of Motorcycle Maintenance: An Inquiry into Values, 1974)

Recognition

This thesis, like all scientific research, was not accomplished alone. Many colleagues at the LIVIA laboratory, UNESP Bauru (Brazil), and the Motor Learning and Performance research group at VU Amsterdam provided invaluable feedback during my Doctorate. To each of you, I dedicate my heartfelt thanks. However, there are some people who deserve explicit acknowledgment. Completing this Doctorate took longer than expected. Challenges such as a pandemic, battles with anxiety, and undiagnosed ADHD imposed significant restrictions on my progress. Luckily, I have been surrounded by very special people, whose support kept me going. For them, I hold the deepest gratitude and admiration.

First, I have two special contributors to thank. Allow me to introduce you to these two wonderful beings who have enriched my life and PhD journey:



Ms. Caetano José Chiozi

Nickname: Caê ou Bebezão
Favourite food: any
Favourite activity: going for a walk!



Ms. Granite Bouzard

Nickname: Bebe (he doesn't like)
Favourite food: salmon
Favourite activity: sleep

Without their emotional support, my life and this thesis would be far less fulfilling. Eu te amo, meu bebezão Caê. Je t'aime, mon bébé Granite. 😊

R1. Acknowledgement

There is no other way to start than by expressing my deepest gratitude to my mom, Cristina, and my grandma, Maria. They were always there for me, even when I didn't believe in myself. My grandma comes from a humble farming family, learning from an early age the hard lessons of labour responsibilities, the constraints imposed on women by this sexist society, and the harsh realities of social inequality. Her childhood was marked by adversity—abusive parents and even hunger. Her life eased only slightly upon marriage, not because her husband was exceptional (especially in 1970s Brazil), but because it brought her a little of freedom. I could write an entire book with her life story, but that is not my purpose here. This brief contextualisation is to illustrate that she, regrettably, lacked access to education. In the countryside, she worked on the coffee farm; when the family migrated to the city, she laboured as a housekeeper until she retired. Despite never being surrounded by books, she always pointed out the value of education to me. Education meant existence and freedom, the ability to achieve anything. In her words, "You have to study, Gisele... to become someone in life." This, from a woman denied education and freedom for so long. Now older and wiser, I understand her perspective—a consequence of years of societal neglect. Illiterate, she faced discrimination throughout her life. I deeply admire you, grandma — your strength, resilience, and persistence.

You have taught me precious lessons that no book can teach. Thank you for always supporting me. This PhD is ours. I love you, grandma.

Given my grandma's history, it's easy to see my mom as another strong and independent woman. Indeed, she is undoubtedly another pillar of strength in my life. The statement "without her, this thesis wouldn't exist" is literal truth. In fact, my entire academic journey owes its existence not just to her financial support, but more importantly, to her unconditional psychological support. She has been there for me, tirelessly, teaching me day-by-day what love is. Mom also had a tough life — born into rural life, she spent her childhood and adolescence working alongside my grandma on the farm. In the city, she sewed in factories and hospitals. She worked long hours, sacrificing weekends, all to give me the opportunities she never had. She started school in the countryside but only finished it later in life. When I was in elementary school and came home with homework she couldn't assist with. She decided to do a "supletivo"—an accelerated education program for individuals who did not complete their primary or secondary education within the standard timeframe. Yes, she went back to school for loving me, and for loving you, mom, I am finishing this Doctorate. You daughter is now a Doctor of Philosophy. Every suffering, every sleepless night, every financial struggle – it's all worth it now. Everything is possible because you chose me. You chose me when you were left pregnant by my father. You chose me when I faced health problems in my childhood. You chose me when I left home to play volleyball and after going to college. You chose me when I "came out of the closet" as a lesbian. You chose me when I went to live abroad. You've always stood by me, and I promise you'll always be with me. I am an extension of you in this world. This Doctorate is yours too. Thank you for everything, Mom. I love you forever.

Fortunately, life brings us people not bound by blood but who remind me of the true essence of love. During my years in Bauru, I made many friends, but Matheus (or Matheusão) deserves explicit thanks. As a member of the laboratory LIVIA and a volleyball player, it's easy to see how we got along so well. But our friendship has lasted so long also because we are evolving together. Matheus, when you visited me in Rouen, I saw how mature you have become while still keeping the same "childish" spirit. Your smile captivates everyone around you. Thank you for being my best lab-mate. We are proof that education changes lives, and I am immensely proud of you. I admire you as a scientist, a teacher, and above all, as a human being.

During my time in Amsterdam, I met many wonderful people, but none as special as Ruby Sommers. We met through Tinder, and what was supposed to be a date became a great friendship. She was crucial to me during the COVID lockdown, always there for walks and talks when I needed. As a good Amsterdammer, she is certainly one of those responsible for me falling in love with the city of bicycles. Ruby, thank you for all the moments we've shared. Even though we live far from each other, I always find myself smiling when I remember you. I hope our friendship continues for many years to come.

I have a recent friend, but as special as the others. Guillaume is a typical Frenchman but with a unique character and immense heart. I often tell him he brings light wherever he goes, spreading smiles. Guillaume is also an academic, but a good one! Egoless and with a thirst for knowledge, he has taught me the importance of valuing what truly matters in life. He is also a talented artist and able to touch people with his music and poetry. Thank you, Guillaume, for showing me the artistic side of science. I hope our friendship lasts forever.

I also want to thank my girlfriend, Emma. Thank you for understanding when I stay late in the lab or when I need to work on the weekends. Thank you for supporting me during my anxiety crises and to not letting me to give up. Writing for a writer as talented as you is a challenge, but this moment calls for acknowledgment of your presence in my life. I feel like I am trying to tell you the most important thing I've ever said, at the very moment that the ship is pulling away from the dock. I want to skip the cliché things, because I already say them to you every day. Instead, I know this: I love loving you. You've taught me many things, but one

of the most important is that love isn't a feeling – it's a series of actions. Love means you are fully committed to learning, growing and becoming the best version of yourself. Love means you forgive every day and choose to see the good in each other when it's easier to see the bad. Love means you devote yourself to the life-long practice of loving. Love, to me, means you, Emma Laforge. Je t'aime.

Last but certainly not least, I would like to extend my heartfelt gratitude to my supervisors: Dr. John van der Kamp, Prof. Dr. Sérgio Tosi Rodrigues, and Dr. Martina Navarro. John is a person I deeply respect. He is politically active, exceptionally critical, and authentic. He is, without a doubt, one of the most intelligent people I have ever met. One of John's remarkable abilities is his skill in adapting his communication to effectively engage with diverse audiences. Whether speaking to an undergraduate student, myself, or a senior professor, he never underestimates or overestimates anyone, maintaining a captivating dialogue. He always has a book recommendation for me, often related to communism or politics, knowing my interests well. This intellectual engagement has been a significant source of inspiration for me. During my Ph.D. journey, I almost gave up, and John was instrumental in my decision to persevere. He sees and treats his students as humans, not machines, a rare quality in academia. During the COVID lockdown, when I was in Amsterdam, away from my family, John's support was crucial. I remember receiving couple of emails from him, checking in on me and inviting me for coffee. These gestures, though seemingly small, were incredibly meaningful during that vulnerable time. As a scientist, John is a profound inspiration. He is egoless and has taught me the true essence of being a researcher. I recently read a book that adapted Aristotle's famous quote, "Dear to me is Plato, dearer still is truth," to Gibsonian psychology. The author states, "Gibson is dear to me, but dearer still is truth" (Favela, 2014, preface). This sentiment encapsulates one of John's crucial lessons to me: while it is important to recognize our sources of inspiration, we must remain steadfastly committed to the evidence. Thank you, John, for these and many other life lessons. You are an incredible human being and, if I may say, a friend. I hope our friendship and collaboration continue for many years to come.
My story with Sérgio began before I started my PhD. In 2012, I joined the Laboratory of Information, Vision, and Action (LIVIA) under the guidance of Professors Sérgio and Paula Polastri. They nurtured my early steps in science and sparked my passion for the field. Sérgio is someone I greatly admire. I can easily picture myself sharing a coffee or a beer with him, engaging in conversations that inevitably end up on politics or science. It is easy to like Sérgio, a simple and easy-going person, with an enormous heart. The difficulty is to answer his questions. Known for always asking difficult questions, Sérgio always encouraged me to ask questions in public. Or worse, he always "filled" me with questions. However, it didn't take long for me to understand that those dreaded questions were actually helping me evolve, not only as a scientist, but as a human being. One of the lessons he taught me is the importance of recognizing progress and having faith in the process. Probably this mindset comes from his experience in Karate, where the idea of persevering (OSS) during exhaustion equips the athlete to handle stressful situations. Thank you, Sérgio, for all the academic and life lessons. Your support and trust in me were essential for me to persevere. The PhD journey was arduous but having you as my mentor made all the difference. I hope our collaboration and friendship continue for many years to come.

I must also extend my heartfelt gratitude to Martina Navarro, my co-supervisor from the University of Portsmouth (UK). Since our first meeting in 2014/2015, Martina has been a constant source of inspiration. Whether as an athlete, researcher, or friend, Martina goes to great lengths to achieve her goals and help others. Like Sérgio, Martina saw potential in me countless times and offered unwavering support throughout my journey. Several times during my doctorate, I received messages from her saying "If you need to talk, let me know and we do a zoom call". As a woman, I cannot fail to mention my admiration to Martina's work in sport

science. Thank you, Martina, for always supporting me and for all valuable advice. I look forward to continuing our partnership and friendship.

These simple words cannot fully capture my feelings and gratitude for the incredible people mentioned here. I wanted though to acknowledge each of you in my PhD thesis as a symbol of my appreciation. This dream is becoming true, and each of you has played a special role in it. You will always have a place in my heart. Thank you so much for everything. I look forward to hugging each of you soon.

Cheers,
Gisele

R2. Agradecimentos

Não há outra maneira de começar senão expressando minha mais profunda gratidão à minha mãe, Cristina, e à minha avó, Maria. Elas sempre estiveram ao meu lado, mesmo quando eu não acreditava em mim mesma. Minha avó vem de uma família humilde de agricultores, aprendendo desde cedo as duras lições das responsabilidades do trabalho, as restrições impostas às mulheres por esta sociedade sexista e as duras realidades da desigualdade social. Sua infância foi marcada pela adversidade — pais abusivos e até fome. Sua vida melhorou apenas um pouco após o casamento, não porque seu marido fosse excepcional (especialmente no Brasil dos anos 1970), mas porque lhe trouxe um pouco de liberdade. Eu poderia escrever um livro inteiro com a história de sua vida, mas esse não é meu objetivo aqui. Esta breve contextualização é para ilustrar que ela, lamentavelmente, não teve acesso à educação. No campo, ela trabalhou na fazenda de café; quando a família migrou para a cidade, ela trabalhou como empregada doméstica até se aposentar. Apesar de nunca ter sido cercada por livros, ela sempre me apontou o valor da educação. Educação significava existência e liberdade, a capacidade de alcançar qualquer coisa. Em suas palavras, "Você tem que estudar, Gisele... para se tornar alguém na vida." Isto, vindo de uma mulher que foi negada à educação e à liberdade por tanto tempo. Agora, mais velha e sábia, entendo sua perspectiva — consequência de anos de negligência social. Analfabeta, ela enfrentou discriminação ao longo de sua vida. Eu te admiro profundamente, vó — sua força, resiliência e persistência. Você me ensinou lições preciosas que nenhum livro pode ensinar. Obrigada por sempre me apoiar. Este doutorado é nosso. Eu te amo, vó.

Dada a história da minha avó, é fácil ver minha mãe como outra mulher forte e independente. De fato, ela é, sem dúvida, outro pilar de força em minha vida. A afirmação "sem ela, esta tese não existiria" é a pura verdade. Na verdade, toda a minha jornada acadêmica deve sua existência não apenas ao seu apoio financeiro, mas, mais importante, ao seu apoio psicológico incondicional. Ela sempre esteve ao meu lado, incansavelmente, ensinando-me dia após dia o que é amor. Mamãe também teve uma vida difícil — nascida no campo, ela passou sua infância e adolescência trabalhando ao lado da minha avó na fazenda. Na cidade, ela costurava em fábricas e hospitais. Trabalhou longas horas, sacrificando fins de semana, tudo para me dar as oportunidades que ela nunca teve. Ela começou a escola no campo, mas só terminou mais tarde na vida. Quando eu estava no ensino fundamental e voltava para casa com lições de casa que ela não podia ajudar, ela decidiu fazer um "supletivo" — um programa de educação acelerada para pessoas que não concluíram o ensino fundamental ou médio dentro do prazo padrão. Sim, ela voltou para a escola por amor a mim, e por amor a você, mãe, estou terminando este doutorado. Sua filha agora é Doutora em Filosofia, mãe. Todo sofrimento, toda noite sem dormir, toda luta financeira — tudo valeu a pena agora. Tudo é possível porque você me escolheu. Você me escolheu quando foi deixada grávida pelo meu pai. Você me escolheu quando enfrentei problemas de saúde na minha infância. Você me escolheu quando saí de casa para jogar vôlei e depois fui para a faculdade. Você me escolheu quando eu "saí do armário" como lésbica. Você me escolheu quando fui morar no exterior. Você sempre esteve ao meu lado, e prometo que você sempre estará comigo. Eu sou uma extensão de você neste mundo. Este doutorado é seu também. Obrigada por tudo, mãe. Eu te amo para sempre.

Felizmente, a vida nos traz pessoas não ligadas pelo sangue, mas que me lembram da verdadeira essência do amor. Durante meus anos em Bauru, fiz muitos amigos, mas Matheus (ou Matheusão) merece um agradecimento explícito. Como membro do laboratório LIVIA e jogador de vôlei, é fácil ver como nos demos tão bem. Mas nossa amizade durou tanto também porque estamos evoluindo juntos. Matheus, quando você me visitou em Rouen, vi como você se tornou maduro enquanto mantém o mesmo espírito "infantil". Seu sorriso cativa todos ao seu redor. Obrigada por ser meu melhor companheiro de laboratório. Somos prova de que a

educação muda vidas, e estou imensamente orgulhosa de você. Eu te admiro como cientista, professor e, acima de tudo, como ser humano.

Durante meu tempo em Amsterdã, conheci muitas pessoas maravilhosas, mas nenhuma tão especial quanto Ruby Sommers. Nós nos conhecemos através do Tinder, e o que deveria ser um encontro se tornou uma grande amizade. Ela foi crucial para mim durante o confinamento da COVID, sempre presente para passeios e conversas quando eu precisava. Como uma boa moradora de Amsterdã, ela é certamente uma das responsáveis por eu ter me apaixonado pela cidade das bicicletas. Ruby, obrigada por todos os momentos que compartilhamos. Embora vivamos longe uma da outra, sempre me pego sorrindo quando lembro de você. Espero que nossa amizade continue por muitos anos.

Tenho um amigo recente, mas tão especial quanto os outros. Guillaume é um típico francês, mas com um caráter único e um coração imenso. Muitas vezes digo a ele que ele traz luz aonde quer que vá, espalhando sorrisos. Guillaume também é um acadêmico, mas um bom! Sem ego e com sede de conhecimento, ele me ensinou a importância de valorizar o que realmente importa na vida. Ele também é um artista talentoso, capaz de tocar as pessoas com sua música e poesia. Obrigada, Guillaume, por me mostrar o lado artístico da ciência. Espero que nossa amizade dure para sempre.

Também quero agradecer à minha namorada, Emma. Obrigada por entender quando fico até tarde no laboratório ou quando preciso trabalhar nos fins de semana. Obrigada por me apoiar durante minhas crises de ansiedade e por não me deixar desistir. Escrever para uma escritora tão talentosa quanto você é um desafio, mas este momento pede o reconhecimento de sua presença em minha vida. Sinto como se estivesse tentando lhe dizer a coisa mais importante que já disse, no exato momento em que o navio está se afastando do cais. Quero pular as coisas clichês, porque já digo isso a você todos os dias. Em vez disso, sei disso: eu amo amar você. Você me ensinou muitas coisas, mas uma das mais importantes é que o amor não é um sentimento – é uma série de ações. Amar significa que você está totalmente comprometido em aprender, crescer e se tornar a melhor versão de si mesmo. Amar significa perdoar todos os dias e escolher ver o bem um no outro quando é mais fácil ver o mal. Amar significa devotar-se à prática contínua do amor. Amar, para mim, significa você, Emma Laforge. Je t'aime.

Por último, mas certamente não menos importante, gostaria de estender minha sincera gratidão aos meus supervisores: Dr. John van der Kamp, Prof. Dr. Sérgio Tosi Rodrigues e Dr. Martina Navarro. John é uma pessoa que respeito profundamente. Ele é politicamente ativo, excepcionalmente crítico e autêntico. Ele é, sem dúvida, uma das pessoas mais inteligentes que já conheci. Uma das habilidades notáveis de John é sua capacidade de adaptar sua comunicação para envolver efetivamente diversos públicos. Seja falando com um estudante de graduação, comigo ou com um professor sênior, ele nunca subestima ou superestima ninguém, mantendo um diálogo cativante. Ele sempre tem uma recomendação de livro para mim, muitas vezes relacionada ao comunismo ou política, conhecendo bem meus interesses. Este engajamento intelectual tem sido uma fonte significativa de inspiração para mim. Durante minha jornada de doutorado, quase desisti, e John foi fundamental na minha decisão de perseverar. Ele vê e trata seus alunos como seres humanos, não como máquinas, uma qualidade rara na academia. Durante o confinamento da COVID, quando eu estava em Amsterdã, longe da minha família, o apoio de John foi crucial. Lembro-me de receber alguns e-mails dele, verificando como eu estava e me convidando para um café. Esses gestos, embora aparentemente pequenos, foram incrivelmente significativos durante aquele momento vulnerável. Como cientista, John é uma profunda inspiração. Ele não tem ego e me ensinou a verdadeira essência de ser pesquisador. Recentemente li um livro que adaptou a famosa citação de Aristóteles, "Querido é Platão, mais querida ainda é a verdade", para a psicologia gibsoniana. O autor afirma: "Gibson é querido para mim, mas mais querida ainda é a verdade" (Favela, 2014, prefácio). Este sentimento encapsula uma das lições cruciais de John para mim: embora seja importante reconhecer nossas

fontes de inspiração, devemos permanecer firmemente comprometidos com as evidências. Obrigada, John, por estas e muitas outras lições de vida. Você é um ser humano incrível e, se me permite dizer, um amigo. Espero que nossa amizade e colaboração continuem por muitos anos.

Minha história com Sérgio começou antes de eu iniciar meu doutorado. Em 2012, ingressei no Laboratório de Informação, Visão e Ação (LIVIA) sob a orientação dos professores Sérgio e Paula Polastri. Eles nutriram meus primeiros passos na ciência e despertaram minha paixão pelo campo. Sérgio é alguém que admiro muito. Posso facilmente me imaginar compartilhando um café ou uma cerveja com ele, envolvendo-me em conversas que inevitavelmente terminam em política ou ciência. É fácil gostar do Sérgio, uma pessoa simples e descontraída, com um enorme coração. A dificuldade é responder às suas perguntas. Conhecido por sempre fazer perguntas difíceis, Sérgio sempre me incentivou a fazer perguntas em público. Ou pior, ele sempre me "encheu" de perguntas. No entanto, não demorou muito para eu entender que essas perguntas temidas estavam na verdade me ajudando a evoluir, não apenas como cientista, mas como ser humano. Uma das lições que ele me ensinou é a importância de reconhecer o progresso e ter fé no processo. Provavelmente essa mentalidade vem de sua experiência no Karate, onde a ideia de perseverar (OSS) durante a exaustão equipa o atleta para lidar com situações estressantes. Obrigada, Sérgio, por todas as lições acadêmicas e de vida. Seu apoio e confiança em mim foram essenciais para eu perseverar. A jornada de doutorado foi árdua, mas ter você como meu mentor fez toda a diferença. Espero que nossa colaboração e amizade continuem por muitos anos.

Devo também estender minha sincera gratidão a Martina Navarro, minha co-supervisora da Universidade de Portsmouth (Reino Unido). Desde nosso primeiro encontro em 2014/2015, Martina tem sido uma fonte constante de inspiração. Seja como atleta, pesquisadora ou amiga, Martina vai longe para alcançar seus objetivos e ajudar os outros. Assim como Sérgio, Martina viu potencial em mim inúmeras vezes e ofereceu apoio inabalável ao longo da minha jornada. Várias vezes durante meu doutorado, recebi mensagens dela dizendo "Se precisar conversar, me avise e fazemos uma chamada no Zoom". Como mulher, não posso deixar de mencionar minha admiração pelo trabalho de Martina em ciência do esporte. Obrigada, Martina, por sempre me apoiar e por todos os conselhos valiosos. Espero continuar nossa parceria e amizade.

Estas simples palavras não podem capturar totalmente meus sentimentos e gratidão pelas pessoas incríveis mencionadas aqui. Quis, no entanto, reconhecer cada um de vocês na minha tese de doutorado como um símbolo da minha apreciação. Este sonho está se tornando realidade, e cada um de vocês desempenhou um papel especial nele. Vocês sempre terão um lugar no meu coração. Muito obrigada por tudo. Estou ansiosa para abraçar cada um de vocês em breve.

Saúde,
Gisele

R3. Dankwoord

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Proost,
Gisele

Thesis in one A4

GOTARDI, G. C. **Visually guided actions of urban traffic users: towards an affordance-based approach.** 2024. 206p. Thesis (Doctorate in Human Movement Sciences)- UNESP, Faculty of Sciences, Bauru, 2024.

T1. Abstract

This thesis investigates visually guided actions of urban traffic users, specifically drivers and cyclists, through different theoretical frameworks. It is divided into two parts, each employing distinct guides to discovery.

Part 1: The focus is on drivers' gaze behaviour during virtual navigation grounded in cognitivist approaches. Three experiments investigate the relationship between visual attention and driving performance among vulnerable driver groups. Study 1 explores the impact of anxiety on attention and performance in driving, revealing that while anxiety impairs processing efficiency and performance effectiveness for both inexperienced and experienced drivers, it shows that attentional shifts differ based on experience level. Study 2 investigates how race gaming experience influences gaze behaviour and driving performance, showing that drivers with gaming experience allocate more attention to task-relevant source of information, highlighting how virtual experience can be used as good training for enhancing gaze behaviour and driving performance. Study 3 examines gaze behaviour and driving performance among drivers with Parkinson's disease (PD) and healthy older and younger adults, finding that PD affects performance and gaze behaviour negatively. PD drivers had more collisions and spent less time within the speed zone. Their gaze behaviour was more random, with increased fixations on irrelevant areas and higher visual entropy. Older drivers concentrated their visual search on the lane to detect threats.

Part 2: I shift my guide to discovery to the ecological concept of affordances, investigating the role of perceiving affordances in movement control. Study 4 investigates whether the visual control of braking in cycling is affordance-based. Maximum achievable deceleration was manipulated by adding weights to the bike, and two approach distances are used to vary speed. Participants increased brake adjustments as they approached the action boundary, indicating an affordance-based control strategy. Active cyclists predominantly used the aggressive style, suggesting experience influences braking strategies. Finally, Study 5 explores action scaling in braking relative to preferred and maximum deceleration in cycling on different terrain slopes. Participants began braking earlier with lower deceleration on the downhill slope. Aggressive braking style was more prevalent during the uphill than the downhill slope. Both styles adjust braking magnitude as deceleration increases, supporting the affordance-based approach.

In summary, this thesis advances our understanding of visually guided actions in urban traffic through the study of different theoretical frameworks. Due to its greater ecological representativity and more parsimonious explanation, the affordance-based control approach emerges as the most appropriate perspective for investigating visual perception-action coupling in traffic navigation.

GOTARDI, G. C. **Ações guiadas visualmente por usuários do trânsito urbano: em direção a uma abordagem baseada em affordance**. 2024. 206p. Tese (Doutorado em Ciências da Motricidade)- UNESP, Faculdade de Ciências, Bauru, 2024.

T2. Resumo

Esta tese investiga ações guiadas visualmente de usuários do tráfego urbano, especificamente motoristas e ciclistas, através de diferentes estruturas teóricas. Está dividida em duas partes, cada uma empregando guias distintos para a descoberta.

Parte 1: O foco está no comportamento do olhar dos motoristas durante a navegação virtual, fundamentado em abordagens cognitivistas. Três experimentos investigam a relação entre atenção visual e desempenho na condução entre grupos vulneráveis de motoristas. O Estudo 1 explora o impacto da ansiedade na atenção e no desempenho na direção, revelando que, enquanto a ansiedade prejudica a eficiência do processamento e a eficácia do desempenho tanto para motoristas inexperientes quanto experientes, mostra que os deslocamentos atencionais diferem com base no nível de experiência. O Estudo 2 investiga como a experiência em jogos de corrida influencia o comportamento do olhar e o desempenho na direção, mostrando que motoristas com experiência em jogos dedicam mais atenção a fontes de informação relevantes para a tarefa, destacando como a experiência virtual pode ser usada como um bom treinamento para melhorar o comportamento do olhar e o desempenho na direção. O Estudo 3 examina o comportamento do olhar e o desempenho na direção entre motoristas com doença de Parkinson (DP) e adultos mais velhos e mais jovens saudáveis, constatando que a DP afeta negativamente o desempenho e o comportamento do olhar. Motoristas com DP tiveram mais colisões e passaram menos tempo dentro da zona de velocidade. Seu comportamento do olhar foi mais aleatório, com fixações aumentadas em áreas irrelevantes e maior entropia visual. Motoristas mais velhos concentraram sua busca visual na pista para detectar ameaças.

Parte 2: Eu mudo meu guia de descoberta para o conceito ecológico de affordances, investigando o papel da percepção de affordances no controle do movimento. O Estudo 4 investiga se o controle visual da frenagem no ciclismo é baseado em affordances. A desaceleração máxima atingível foi manipulada adicionando pesos à bicicleta, e duas distâncias de aproximação foram usadas para variar a velocidade. Os participantes aumentaram os ajustes de frenagem à medida que se aproximavam do limite de ação, indicando uma estratégia de controle baseada em affordances. Ciclistas ativos usaram predominantemente o estilo agressivo, sugerindo que a experiência influencia as estratégias de frenagem. Finalmente, o Estudo 5 explora a escala de ação na frenagem relativa à desaceleração preferida e máxima no ciclismo em diferentes inclinações de terreno. Os participantes começaram a frear mais cedo com menor desaceleração na inclinação descendente. O estilo de frenagem agressivo foi mais prevalente durante a inclinação ascendente do que na descendente. Ambos os estilos ajustam a magnitude da frenagem à medida que a desaceleração aumenta, apoiando a abordagem baseada em affordances.

Em resumo, esta tese avança nossa compreensão das ações guiadas visualmente no tráfego urbano através do estudo de diferentes estruturas teóricas. Devido à sua maior representatividade ecológica e explicação mais parcimoniosa, a abordagem de controle baseada em affordances emerge como a perspectiva mais apropriada para investigar o acoplamento percepção-ação visual na navegação do tráfego.

GOTARDI, G. C. **Visueel geleide acties van stadsverkeersgebruikers: naar een op Affordance gebaseerde aanpak.** 2024. 206p. Thesis (Doctoraat in Motriciteitswetenschappen) – UNESP, Faculteit Wetenschappen, Bauru, 2024.

T3. Samenvatting

Deze scriptie onderzoekt visueel geleide acties van stedelijke verkeersgebruikers, specifiek bestuurders en fietsers, door chaal van verschillende theoretische kaders. Het is verdeeld in twee delen, elk met een eigen gids voor ontdekking.

Deel 1: De focus ligt op het kijkgedrag van bestuurders tijdens virtuele navigatie, gebaseerd op cognitieve benaderingen. Drie experimenten onderzoeken de relatie tussen visuele aandacht en rijprestaties bij kwetsbare bestuurdersgroepen. Studie 1 onderzoekt de impact van angst op aandacht en prestaties tijdens het rijden, en onthult dat angst de verwerkings efficiëntie en de prestatie-effectiviteit van zowel onervaren als ervaren bestuurders schaadt, terwijl aandacht verschuivingen verschillen op basis van ervaringsniveau. Studie 2 onderzoekt hoe ervaring met racegames het kijkgedrag en de rijprestaties beïnvloedt, en toont aan dat bestuurders met game-ervaring meer aandacht besteden aan taakrelevante informatiebronnen, wat benadrukt hoe virtuele ervaring kan worden gebruikt als goede training om kijkgedrag en rijprestaties te verbeteren. Studie 3 onderzoekt het kijkgedrag en de rijprestaties van bestuurders met de ziekte van Parkinson (PD) en gezonde oudere en jongere volwassenen, waarbij blijkt dat PD de prestaties en het kijkgedrag negatief beïnvloedt. PD-bestuurders hadden meer aanrijdingen en brachten minder tijd door binnen de snelheidszone. Hun kijkgedrag was willekeuriger, met meer fixaties op irrelevante gebieden en hogere visuele entropie. Oudere bestuurders concentreerden hun visuele zoektocht op de rijbaan om bedreigingen te detecteren.

Deel 2: Ik verschuif mijn gids voor ontdekking naar het ecologische concept van affordances, waarbij ik de rol van het waarnemen van affordances in bewegingscontrole onderzoek. Studie 4 onderzoekt of de visuele controle van remmen bij fietsen gebaseerd is op affordances. De chaal haalbare vertraging werd gemanipuleerd door gewichten aan de fiets toe te voegen en er chaal twee benaderingsafstanden gebruikt om de snelheid te variëren. De deelnemers verhoogden de rem aanpassingen naarmate ze de actieboundary naderden, wat wijst op een op affordances gebaseerde controle strategie. Actieve fietsers gebruikten voornamelijk de agressieve stijl, wat suggereert dat ervaring de remstrategieën beïnvloedt. Tot slot onderzoekt Studie 5 de actie chaal in remmen ten opzichte van de voorkeur en maximale vertraging bij fietsen op verschillende terreins hellingen. De deelnemers begonnen eerder te remmen met een lagere vertraging op de helling naar beneden. De agressieve remstijl was meer prevalent tijdens de helling omhoog dan omlaag. Beide stijlen passen de remkracht aan naarmate de vertraging toeneemt, wat de op affordances gebaseerde benadering ondersteunt.

Samenvattend, deze scriptie verbetert ons begrip van visueel geleide acties in stedelijk verkeer door de studie van verschillende theoretische kaders. Vanwege zijn grotere ecologische representativiteit en meer beknopte uitleg, blijkt de op affordances gebaseerde controle benadering de meest geschikte perspectief te zijn voor het onderzoeken van visuele perceptie-actie koppeling in verkeersnavigatie.

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Chapter 1.

General Introduction

Navigating through traffic is a complex task. Imagine that you are a cyclist approaching a crowdy intersection. Visual perception becomes paramount as you meticulously need to scan the environment, identifying opportune moments for crossing. Concomitantly, you must be able to direct your attention towards relevant sources of information such as the traffic lights and the road, while filter out distractions such as noise or advertising posters. Balance and motor coordination are also essential during crossing, as is synchronizing your pace with the traffic flow and adaptative responding to emerging hazards or opportunities in the environment. Yet, navigating traffic tend to be done with certain ease by people every day. In contrast, the scientific understanding of the intrinsic relationship between perception and action in dynamic environments is often arduous.

In this thesis, I aim to investigate how visual perception is used to guide actions in the context of urban traffic, particularly for drivers and cyclists. To this extend, I delve into different theoretical frameworks, experimental setups, hypotheses testing, and data analyses that allowed me to explore distinct guides to discovery. In science, guides to discovery refers to principles or methodologies that assist researchers to ask questions, formulate hypotheses and understand phenomena (CHEMERO, 2009). The concept of affordance (GIBSON, 1979), for example, is a common guide to discovery among ecological researchers to understand perception and action, in which the measurement of gaze behaviours may help uncover the information that underpin (visual) perception-action coupling. By contrast, cognitive psychologists would interpret, gaze behaviour as an indication of the internal cognitive processes and attentional control that regulate actions. Therefore, before presenting the research conducted for my Doctorate, I introduce the theoretical frameworks for investigating the visually guided actions of urban traffic users.

1.1. Theoretical frameworks of visually guided actions

The role of visual perception in the control of action has been a target of scientific inquiry for centuries (DESCARTES, 1633; FAJEN, 2002; GIBSON, 1950, 1958, 1979; HELMHOLTZ, 1866; LAND, 2006; LEE, 1976; MARR, 1982; MILNER; GOODALE, 1995; VICKERS, 1997; WILLIAMS et al., 1999). Visually guided actions refer to a class of behaviours characterized by continuous and prospective control, primarily guided on the basis of visual information (FAJEN, 2005B, 2007; GIBSON, 1958, 1979; HARRISON et al., 2016; LAND, 2006; WARREN; WHANG, 1987). One of the pioneering papers investigating the visual guidance of action is “Visually controlled locomotion and visual orientation in animals” by James J. Gibson, published in 1958. In this remarkable paper, Gibson not only introduced fundamental concepts of his ecological theory of perception (GIBSON, 1979) but also provided "formulae" for various locomotor tasks, including steering towards a goal and approaching without collision. At the core of the paper is the hypothesis that optic flow provides the necessary information for the control of locomotion within the environment (GIBSON, 1958). According to Gibson (1958), the light reaching the observer’s eyes is composed of a structured pattern, encompassing nested solid angles formed by objects and places of the environment projecting at the point of observation. This structured pattern of light is called the optic array (figure 1a). As the observer moves, and thus goes from one point of observation to another, then this creates a changing optic array, as depicted by the solid and dashed lines in Figure 1a,

indicating the shift from a seated to a standing position. Optic flow, then, signifies one type of change of the optic array that specifies a change in the perceiver's position relative to the environment (e.g. standing up, or walking). In other words, optic flow occurs when observers move through their environment. The specific pattern of optic flow depends on the relative motion between the observer and places and objects of the environment. For example, imagine you are riding a bicycle down a street. As you pedal forward, then optically, the pedestrians, trees, signs, and buildings near the street move rapidly past you, while objects in the distance move more slowly. This pattern of optic flow provides the crucial information about your speed and the speed (or stationarity) of other persons and objects of traffic environment. Therefore, optic flow provides the essential visual information to guide navigation through the environment (GIBSON, 1958).

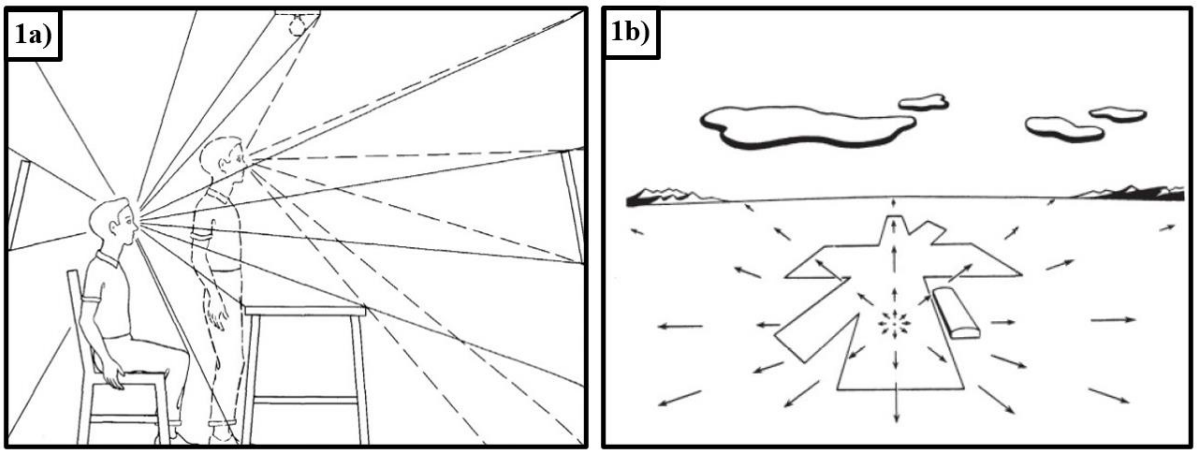


Figure 1: (a) The altered optic array as a result of the observer movement; (b) Optic flow pattern seen by the airplane pilot during landing.

Source: (a) Reprinted from "On the Ambient Optic Array: James Gibson's Insights About the Phenomenon of Chiaroscuro" by Todd (2020), licensed under CC BY 4.0; (b) Reprinted from "Information is Where You Find it: Perception as an Ecologically Well-Posed Problem" by Warren (2021), licensed under CC BY 4.0.

Furthermore, Gibson (1958) offered meticulously designed formulae for a set of locomotor tasks, including steering towards a goal, braking, obstacle avoidance, and pursuit of and flight from moving objects. These principles, later called "laws of control" by Warren (1988), have become and still are very influential in contemporary research on the visual guidance of action (FAJEN, 2005C, 2005A; HIGUCHI et al., 2011; STEINMETZ et al., 2020; WAGMAN et al., 2016; ZHAO; WARREN, 2015). One crucial formula in the visual guidance of locomotion addresses steering toward a stationary goal. Gibson (1958) proposed the focus of expansion: As an observer moves forward, the optic flow pattern expands outward (i.e., outflow) from a central point known as the "focus of expansion". Figure 1b illustrates the outflow pattern from an airline pilot's viewpoint during landing. It shows the focus of expansion that indicates the aircraft's current heading. To land the aircraft successfully, the pilot must move so as keep the focus of expansion close to the point on the runway where the plane is intended to land (GIBSON, 1950; 1958). In other words, the pilot must steer the plane such that information is generated that specifies safe landing.

Gibson's work (1958, 1979) was instrumental in popularizing the study of the visually guided actions in locomotion. Subsequently, various researchers have further developed and refined the Gibsonian perspective on perception and action (FAJEN, 2007; LEE, 1976; MORICE et al., 2015; WARREN; WHANG, 1987; YILMAZ; WARREN, 1995; ZHAO; WARREN, 2015). However, the ecological approach presents itself as a radical alternative to the cognitive view of studying perception and action, which is model-based. Here, models refer to internal representations that are foundational for perception and action. To put this into context, I next provide a brief overview of this model-based control approach. Importantly, the clear contrast between ecological and cognitive approaches facilitates a comprehension of their distinct guides to discovery. I then return to different approaches within the ecological approach that have inspired my Doctorate, including the information-based control and affordance-based control approaches.

Model-based approach

> *"We are never in touch with the present, because neural information-processing itself takes time. So, strictly speaking, what you are experiencing as the present moment is actually the past."*
>
> (METZINGER, 2009, p. 36).

According to the model-based approach, actions are controlled by an internal model that encompasses a three-dimensional representation of the spatial layout of the environment (LOOMIS; BEALL, 2004), grounded in cognitivism[1] (MILLER, 2003; SHANNON, 1948; TURING, 1950). Consequently, behaviour is to be planned, initiated and controlled by the mind, which in cognitivism is considered as an information-processing system, such as a computer (see Figure 2a). In terms of visual perception and action, environmental cues or stimuli create on the retina a two-dimensional image that are inherently meaningless. For instance, the two-dimensional size or shape do not unambiguously inform about an object's size or shape, because that will depend on the distance and orientation relative to the observer. The two-dimensional retinal image is then processed or enriched, in different stages, and most importantly within the visual cortex, where an internal model or *representation* of the external world is formed. The world is then perceived. Next, the model serves as the basis for decision making and the planning and programming of action. Once the action is programmed, commands are sent from the motor cortex to the muscular system to initiate and execute of movements or action.

[1] Cognitivism in psychology found its roots during the cognitive revolution of the mid-20th century. According to George Miller (2003), this revolution could be viewed as a counter movement to the rise of behaviourism. The behaviourist revolution focused on redefining psychology as the study of behaviour. Perception became discrimination, memory became learning, language became verbal behaviour. Simultaneously, the emergent computer science with influential works such as Shannon's (1948) information theory and Turing's (1950) theoretical foundations of computers further inspired the branch of psychology that understands human mind as an information-processing system.

Proponents of the model-based approach argue that the existence of an internal model of the environment is indispensable for guiding actions, particularly during brief interruptions of the optic flow. Studies have demonstrated that individuals can navigate accurately through the environment even under fully blind conditions (GODTHELP, 1985; LOOMIS et al., 1992; PHILBECK et al., 1997). In a walking experiment, Loomis and colleagues (1992) asked participants to briefly look at a target on the ground ahead, then close their eyes and walk without vision towards the remembered target. The accuracy of locating the target at a distance suggests that participants had created an internal model of the target's location that guided the walking to the target (LOOMIS et al., 1992). In driving, similar findings have been observed with temporal visual occlusions. Godthelp (1985) asked drivers to perform lane changes on a straight road in a driving simulator. Two visual conditions were presented: full vision, the simulator screen remained continuously visible; and visual occlusion, the simulator screen was momentarily turned off for one second when the driver approached the lane change zone. In both conditions, participants were able to successfully perform the lane changes (GODTHELP, 1985). These studies of visually directed actions with (temporarily) occluded vision support the hypothesis that actions are programmed on the basis of an internal model of the environment (LOOMIS et al., 1992; PHILBECK; LOOMIS, 1997; GODTHELP, 1985).

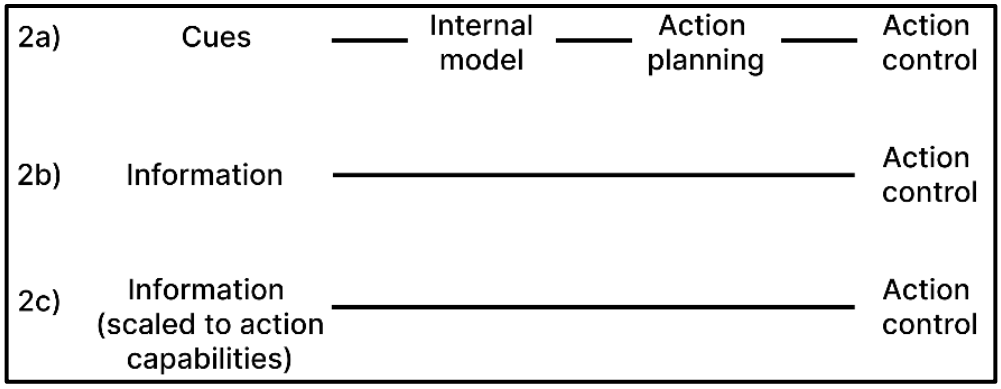


Figure 2*:* Schematic illustration of (a) model-based control; (b) information-based control; (c) affordance-based control.

Source: Modified from Zhao & Warren (2015).

In addition, research grounded in model-based approach assumes critical roles of feedback and feedforward control. For example, Donges (1978) proposed a model of steering that included two levels of control. At the higher cognitive level, a feedforward mechanism operates that relies on a prediction of the curvature of the road ahead, which is obtained by fixating the tangent point of the road (LAND; LEE, 1994). At the lower control level, a feedback mechanism corrects lane position errors, primarily by obtaining information from the near road through peripheral vision. The coordination of both levels culminates in steering control, with the higher level determining the overall strategy and the lower level implementing the motor commands. Figure 3 provides an illustration of the feedforward mechanism. It presents scenarios of successful (Fig. 3a) and unsuccessful performance (Fig 3b). As assumed in model-based approach, the external world and the internal model are dichotomous. Successful performance is achieved whenever the predicted tangent angle (i.e., by the internal

model) matches the road tangent angle (i.e., in the external world), allowing for precise adjustments in the steering wheel angle. Conversely, when there is a disparity between the predicted and road tangent angles, steering control becomes inaccurate, potentially resulting in failure if not corrected by feedback.

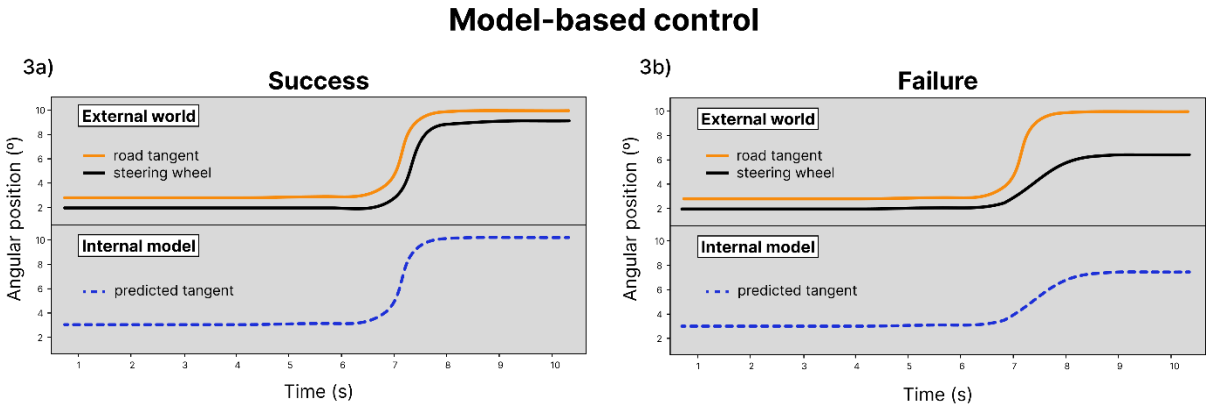


Figure 3: Data from sample trial showing the road tangent angle (orange solid line), steering wheel angle (black solid line), and the predicted tangent angle (blue dashed line) in both (a) successful and (b) unsuccessful performance.

In sum, the model-based approach implies both feedforward and feedback control. This entails control by taking-in perceptual cues, doing computations to create an internal model that serves as a basis for predictions, and then programming and executing actions accordingly.

Information-based approach

> *"Locomotion and manipulation are neither triggered nor commanded but controlled... And they are controlled not by the brain but by information… behavior is regular without being regulated. The question is how this can be."*
>
> (GIBSON, 1979, p. 225).

Gibson's 1958 article pioneers an information-based approach to understanding navigation through the environment, focusing on direct perception rather than cognitive processing. His perspective emphasizes the role of *current information* in guiding action, suggesting a prospective or online control (GIBSON, 1979; ZHAO; WARREN, 2015). That is, action is directly controlled by the information within the optic flow, eliminating the need for an internal model (see Figure 2b). Unlike the visual cues and stimuli in model-based approach, Gibson claimed that information in the optic array is inherently *meaningful* and specifies the objects, places and possibilities for on action of the environment. Specificity implies that information directly maps to the objects and places of the environment, making any further processing redundant. Various studies have identified specifying optical variables,

and proposed laws of control that couple these specifying informational variables to different action (FAJEN; WARREN, 2003; LEE, 1976; SAVELSBERGH et al., 1991; WARREN et al., 2001). For example, Lee (1976) showed that tau or the inverse of the relative rate change of optical angle from an approaching object provides information or specifies time-to-contact, while Savelsbergh et al. (1991) showed hand closure during catching was controlled by this information. This is referred to as the information-based approach to the visual guidance of action.

Two hypotheses are widely accepted in the information-based approach. First, successful performance hinges on an error-nulling mechanism. Each task possesses a current state, representing the actual actions of the individual, and an ideal state, corresponding to the required actions to achieve the task goal. Accordingly, successful performance is achieved by nulling the error between the current state and the ideal state. The second hypothesis complements the first one by claiming that for each task observers rely on a single specifying optical variable, or a particular pattern of optic flow, to attain the ideal state. Such pattern is characterized by some higher-order property of the environment that remains unchanged within the optic flow (i.e., optical invariant).

The tau-dot model of braking, introduced by D. Lee in 1976, supports both the error-nulling and the single-optical-invariant hypotheses. In braking to avoid collision, the current state refers to the vehicle's current rate of deceleration while the ideal state corresponds to the rate of deceleration that brings the observer to a stop at the intended location without any additional brake adjustments (i.e., ideal deceleration, ANDERSEN et al., 1999; FAJEN, 2007). The crucial information for successful braking is the time remaining until contact (i.e., time-to-contact). Lee (1976) demonstrated that the inverse of the rate of change of the optical angle (i.e., φ), specifies the current distance to stopping location (i.e., Z), divided by the current velocity of approach (i.e., V), which corresponds to the current time-to-contact (i.e., TTC). The inverse of the rate of change of the optical angle is referred to as the optical variable *tau* (τ). It is calculated according to the following equation:

$$\tau = \frac{\varphi}{\dot{\varphi}} = -\frac{Z}{v} = TTC \tag{1}$$

The derivative of the current value of τ (Eq. 1), called $\dot{\tau}$ or *tau-dot*, specifies the rate of change in time-to-contact. Lee (1976) mathematically showed that the ideal deceleration (Dideal) to avoid collision can be achieved by keeping $\dot{\tau}$ at approximately -0.5. This is called the constant *tau-dot* strategy and is mathematically expressed as follows:

$$\begin{aligned} if\ \dot{\tau} &< -0.5, +d \\ if\ \dot{\tau} &> -0.5, -d \\ if\ \dot{\tau} &= -0.5, =d \end{aligned} \tag{2}$$

where *d* refers to the current deceleration. If *tau-dot* is less than -0.5, the current deceleration must increase (+ *d*) to prevent a collision. Conversely, if *tau-dot* exceeds -0.5, the current deceleration must decrease (- *d*) to avoid stopping too far ahead of the obstacle. However, when *tau-dot* is -0.5, the current deceleration must remain constant (= *d*), ensuring the vehicle

stops in time. Essentially, any deviation of *tau-dot* from this threshold mandates adjustments in the current deceleration to effectively nullify the deviation.

Figures 4 show examples of the dynamic interplay between current and ideal decelerations in successful (Figure 4a) and unsuccessful braking (Figure 4b). Successful braking is achieved when the difference between current and ideal deceleration is eliminated in time to avoid a collision, i.e., before the stopping location is reached (Figure 4a). Otherwise, if the error persists as the vehicle approaches the obstacle, collision becomes inevitable (Figure 4b), or the stopping location is too far ahead of the obstacle.

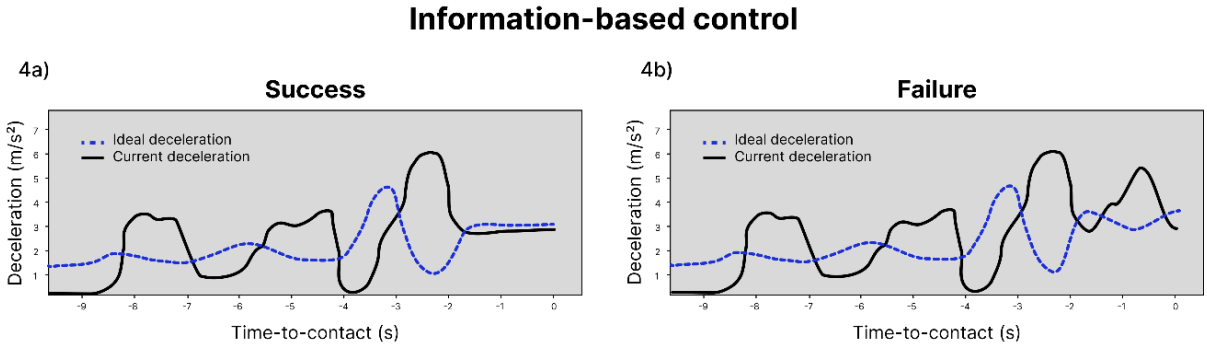


Figure 4: Data from sample trial showing the current deceleration (black solid line) and ideal deceleration (blue dashed line) in both (a) successful and (b) unsuccessful performance.

To summarize, the information-based approach proposes that individuals regulate their actions by continuously detecting current information and coupling it to their movements. That is, task-specific optical variables specify the pattern of optic flow that places the individual in the ideal state, which, if maintained, will result in successful performance (LEE, 1976; YILMAZ; WARREN, 1995; FAJEN, 2005). Although this approach aligns with the ecological theory of perception (GIBSON, 1979), it fails to integrate the key concept of affordance into the visual control of actions.

Affordance-based approach

> *"When the fields of possible behaviors are perceived such as by the driver, the seeing and the doing are merged in the same experience."*
>
> (GIBSON & CROOKS, 1938, p. 460).

Affordances[2] are the possibilities for action that emerge within the relationship between an actor and its immediate surroundings (GIBSON, 1979; STOFFREGEN, 2000; WARREN,

[2] Gibson (1979) defined affordances as "what the environment offers the animal, what it provides or furnishes, either for good or ill." (p. 127). Since then, two main interpretations have been debated in the ecological

1984). For instance, a horizontal, (sufficiently) rigid surface relative to the animal's weight affords support. It then specifies to the animal the possibility of standing upright, walking, running and so on. Hence, perceiving affordances is seeing the environment in terms of what actions can be engaged in. Fajen (2005, 2007) suggests an extension to the information-based approach, highlighting the role of affordances in guiding actions.

In the affordance-based approach (FAJEN, 2007), information guiding action is scaled to the individual's action capabilities (see Figure 2c), in particular to what an actor can maximally achieve. This maximum capability serves as a boundary distinguishing between actions that are possible and those that are impossible (i.e., it requires actions beyond the capability of the actor). In this way, task-specific optical variables, properly scaled to the actor's capabilities, directly specifies the possibilities of action (i.e., affordances). This allows to control the action by moving such that the perception of the affordance of interest is sustained.

Let me return to the task of braking to avoid collisions. As described in Lee's $\dot{\tau}$ model (1976), successful braking is attained if adjustments in current deceleration generate the invariant $\dot{\tau}$ = -0.5 (nulling the error between current and ideal states). However, this information-based control strategy fails to account of the actor's maximum capabilities, such as the maximum deceleration in braking. Consequently, observers relying only on $\dot{\tau}$ to control braking cannot determine whether successful braking is afforded or not. It only tells them what to do, not whether it is possible or not. Fajen's solution to this problem is to propose affordance-based approach: successful performance depends on sustaining the perception of affordances. That is, movements are guided so that the required action to successfully perform the task remains within the limits of one's action capabilities (FAJEN, 2005a, 2005c, 2007). Figures 5 illustrate sample data depicting the control of ideal deceleration[3] in relation to the maximum deceleration in successful (Figure 5a) and unsuccessful braking (Figure 5b) scenarios. Accordingly, current deceleration is controlled so as to keep the ideal deceleration below the maximum deceleration (Figure 5a). Otherwise, if ideal deceleration surpasses the maximum boundary, coming to a stop without collision is no longer possible (Figure 5b).

psychology literature. First, affordances are relations between an animal and its environment that invite behaviour (Warren, 1984; Stoffregen, 2000a; Chemero, 2003; Franchak, 2014). Second, affordances are properties of the environment of an animal that invite behaviour (Lombardo, 1987; Turvey, 1992; Reed, 1996; Heft, 2001). The present thesis aligns with the former interpretation.

[3] Unlike information-based models that admit the ideal state as the only correct control, the affordance-based approach expands the set of actions considered successful, as long as they do not exceed the action boundaries. Therefore, ideal deceleration here should be interpreted as the rate of deceleration required to stop in time. Fajen (2007) appears to have retained the terminology for comparison purposes. So did I.

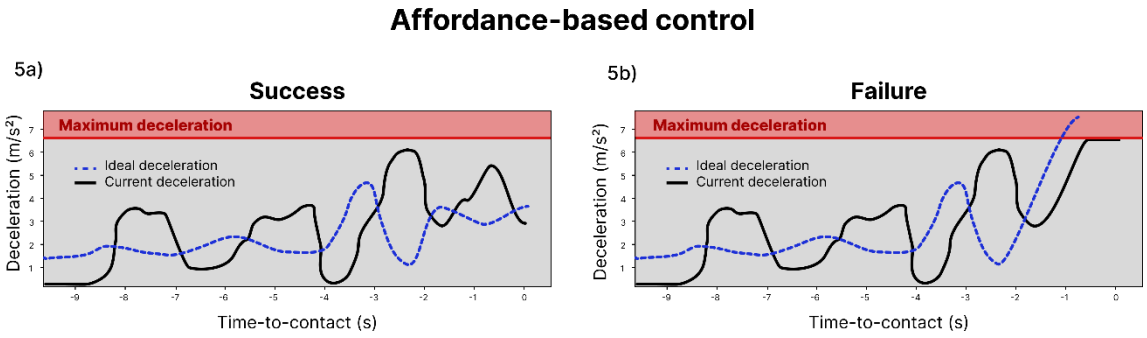


Figure 5: Data from sample trial showing the current deceleration (black solid line) and ideal deceleration (blue dashed line) relative to the maximum deceleration (red horizontal solid line) in both (a) successful and (b) unsuccessful performance.

The second hypothesis posits that the perception of affordances must be recalibrated when there is a change in action capabilities. Calibration involves transforming the metric through which information is perceived, establishing a mapping between information and action (FAJEN, 2007). For example, if a driver perceives Dideal as 40% of Dmax and they are well-calibrated, then Dideal can be maintained under Dmax by applying 40% of the maximum brake pressure. According to Fajen, individuals detect information in units that depend on their action capabilities. Recalibration, therefore, entails adjusting the perceptual metric after changes in action capabilities. If actors get used to performing a task under particular constraints and these constraints suddenly change (e.g. action capabilities change), the specifying information to guide action must be rescaled to the current action capabilities. For example, Scott and Gray (2010) studied perceptual-motor calibration in baseball batting by varying bat weights: standard, lighter, and heavier. Both lighter and heavier groups reduced swing errors within 5-10 trials, adjusting swing velocity and swing onset timing, respectively. Calibration and recalibration are crucial for affordance perception as actions that were previously possible may become impossible, and vice versa (FAJEN, 2005c, 2008). Empirical evidence has supported that individuals take into account their action capabilities to control braking (FAJEN, 2005a, 2005c, 2008). Further description on these studies is presented in chapters 5 and 6 of this thesis. To conclude, affordance-based control advocates that successful performance in visually guided action relies on perceiving the affordances available in the environment and behaving so as to keep the desired action within the range of possible actions.

In sum, the theoretical frameworks of visually guided actions in traffic navigation can be divided into cognitive (model-based) and ecological (information-based or affordance-based) approaches, offering different but not mutually exclusive explanations and guides to discovery. The model-based approach describes visual perception as the process by which the brain interprets the visual information received from the eyes, including the detection of objects, depth perception, and others, often described through gaze behaviour patterns. Conversely, the ecological concept of affordances simplifies the perceptual process by emphasizing the direct detection of action-scaled information from the environment, eliminating the need for cognitive processing and revealing new hypotheses for perception and action research. In the first half of

this thesis, the focus is on understanding how visual perception supports driving in dynamic traffic environments.

1.2. Visual attention in car driving

From a cognitive standpoint, visual perception cannot occur without attentional engagement. Visual attention involves directing cognitive resources toward specific visual stimuli while filtering out less relevant aspects of information (UNDERWOOD et al., 2003, 2011). When navigating in traffic environments, drivers continually shift their focus of attention to accurately perceive the road, traffic signs, and other traffic road users. Within this context, gaze behaviour patterns serve as primary indicators of drivers' visual attention (UNDERWOOD et al., 2003). The eyes continuously scan the environment through fixations and saccades (see Figure 6). This fixation-saccade strategy aims to direct the fovea—the central region of the retina—towards areas of interest in the visual scene. The fovea, rich in cone cells responsible for colour perception and visual acuity (foveal vision), requires continuous reorientation within the changing environment due to its small size (approximately 2°). Fixations occur when the eyes remain relatively still, allowing for detailed information intake, with durations varying between 50-600 milliseconds depending on the task and stimulus characteristics (LAND, 2006). Saccades, rapid eye movements lasting 20 to 40 milliseconds, efficiently relocate the fovea from one point of interest to another within the visual scene (MAHANAMA et al., 2022).

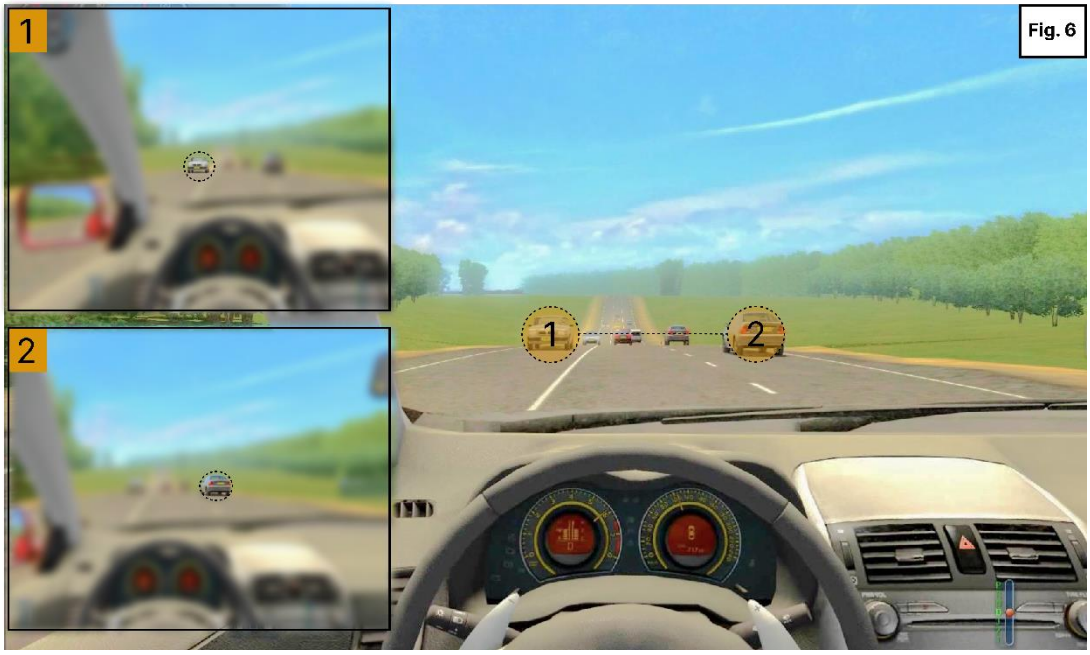


Figure 6: Illustration of the fixations-saccades strategy in driving. The sequence of fixations (orange circles) and saccade (line connecting the orange circles) are presented. Squares 1 and 2 demonstrate the difference in visual acuity between the foveal and extrafoveal areas.

Source: Elaborated by the author using a screenshot from City Car Driving simulator (version 1.5). Based on https://www.tobii.com/resource-center/learn-articles/types-of-eye-movements

The gaze behaviour of drivers has been investigated thoroughly (BEULLENS et al., 2011; CICERI; RUSCIO, 2014; CRUNDALL; UNDERWOOD, 1998; KONSTANTOPOULOS et al., 2010; MOURANT; ROCKWELL, 1972). Most of these studies have been conducted within driving simulators, which offer realistic interactions for users, highly complex traffic scenarios akin to the visual experience of drivers in the natural, out-of-laboratory world (BEULLENS et al., 2011; CICERI; RUSCIO, 2014). Similar methodologies have been employed to study skilled performance in sports (CRAIG, 2013; NEUMANN et al., 2018), physical rehabilitation programs for vulnerable populations such as patients with Parkinson's disease and cerebral palsy (HOWARD, 2017), and the motor learning process (PASCO, 2013).

Vulnerable driver populations refer to groups at higher risk of fatal traffic accidents or impaired driving performance (CLARKE et al., 2005; METZGER et al., 2020). This includes but is not limited to inexperienced drivers, older adults, and individuals with disabilities. Gaze behaviour patterns while driving characterize the level of experience. Inexperienced drivers, especially newly licensed ones, exhibit reduced visual exploration, performing fewer but longer fixations compared to experienced drivers, particularly in hazardous driving conditions such as on highways or during reduced visibility (CRUNDALL; UNDERWOOD, 1998; KONSTANTOPOULOS et al., 2010; UNDERWOOD et al., 2011). Furthermore, inexperienced drivers show fewer fixations to rearview mirrors, suggesting an inability to allocate attentional resources to visual exploration due to the cognitive effort involved in vehicle control (KONSTANTOPOULOS et al., 2010; UNDERWOOD et al., 2003).

Similarly, older drivers demonstrate reduced ability to drive safely. Studies have shown that this population has a reduced effective field of view (OWSLEY, 1998), slower reaction time in dual-task situations (LEVERSEN et al., 2013), and more erratic saccadic eye movements (BEURSKENS; BOCK, 2012), compared to young adult drivers. Yet, older drivers are more susceptible to involvement in a traffic accident (BEURSKENS; BOCK, 2012; OWSLEY, 1998). As the population ages, the prevalence of older drivers and those with age-related diseases such as Parkinson's and Alzheimer's are expected to increase. Consequently, studying the gaze behaviour and performance of these populations is crucial for promoting road safety and reducing traffic accidents and fatalities.

1.3. Outline of the thesis

The current thesis starts by examining drivers' visual attention during traffic navigation. The relationship between gaze behaviour pattern and the risk of accidents in driving has been reported in literature (CRUNDALL; UNDERWOOD, 1998; KONSTANTOPOULOS et al., 2010; UNDERWOOD et al., 2003, 2011). However, the gaze behaviour of certain vulnerable driver groups is still poorly documented. To address this gap, the first part of this thesis – Chapter 1, 2, and 3 – presents original research findings and discussion on this topic.

In **Chapter 2**, I investigate whether, and if so how, the adverse effects of anxiety on visually guided driving can be modulated by experience. Despite growing interest in studying how anxiety impairs performance in the context of sports, few studies have considered to test drivers under pressure (BRIGGS et al., 2011a; MANN et al., 2007). Hence, we examined gaze behaviour and performance in both experienced and inexperienced drivers using a car

simulator. Participants were asked to drive under low- and high-anxiety conditions while their eye movements were recorded. Anxiety was manipulated through competition, the presence of an evaluator, an external video camera, and traffic noise.

Chapter 3 extends the investigation into the influence of driving experience on visual perception and action, comparing groups of drivers and gamers in virtual driving. Racing video game players typically include pre-drivers, active road traffic users such as pedestrians and cyclists intending to become drivers (GATERSLEBEN; HADDAD, 2010). Studies have shown that racing video game players exhibit a high propensity for risky driving behaviours (BEULLENS et al., 2011). However, there is a lack in literature on whether combining natural driving and racing video gaming experiences can enhance gaze behaviour pattern while driving. Participants were divided into drivers with gaming experience, drivers without gaming experience, and gamers without driving experience, and asked to drive in a racing video game circuit as fast as possible while their eye movements were recorded.

In **Chapter 4**, I delve into the detrimental effects of the aging process and Parkinson's disease (PD) on gaze behaviour and driving performance. Studies have demonstrated an impaired performance of older drivers compared to young drivers (LEVERSEN et al., 2013; OWSLEY, 1998), while others have focused on the impacts of PD on driving performance compared to neurologically healthy peers (RIZZO et al., 2010; UC et al., 2006). However, the gaze behaviour of older drivers with PD remains unclear. Therefore, I compare older drivers with PD, older drivers without PD, and young adult drivers without PD in the driving simulator while recording gaze patterns.

The **Interlude** then introduces the second half of the thesis, in which I return to the discussion on the theoretical frameworks of visually guided actions following another guide to discovery. The ecological concept of affordances changes the approach to understanding the perception-action coupling in traffic navigation. Through the scientific principles of parsimony and ecological validity, I analyse how the affordance-based control approach seems to be a more complete alternative account for investigating the visually guided actions of urban traffic users. Subsequently, the second part of this thesis – Chapter 5 and Chapter 6 - is focused on testing the role of affordances in the visual control of braking in cycling.

In **Chapter 5**, I examine whether in an in-situ collision avoidance experiment cyclists regulate braking by adopting an affordance-based control strategy (FAJEN, 2005b, 2005a, 2005c, 2007). To this end, active- and inactive-cyclists were asked to ride a bicycle on a straight path in an indoor gym and stop as close as possible in front of a stationary obstacle. I manipulate the action capabilities, as defined across the person-bicycle system, by adding, unknown to the participants, additional load to the bike, which aims to reduce the maximum deceleration they can achieve (i.e., the maximum action capabilities). We sought evidence whether adaptative brake adjustments would be made relative to maximum achievable deceleration. In addition, we also addressed possible different styles of braking.

Chapter 6 extends the investigation of affordance-based control of the braking of cyclists (FAJEN, 2005b, 2005a, 2005c, 2007). I investigate whether action scaling in braking is relative to preferred and maximum deceleration in cyclists under different terrain slopes. Additionally, I aim to corroborate that braking styles emerge from distinct perceptual-motor calibration. Experienced cyclists were asked to cycle uphill and downhill, coming to a stop within the stopping zone.

Finally, **Chapter 7** or the Epilogue, provides an overview of key findings and implications.

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Chapter 2.

Adverse effects of anxiety on attentional control differ as a function of experience: A simulated driving study

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Abstract

This study tested whether adverse effects of state anxiety on attention and performance may be modulated by experience. Sixteen experienced and eleven inexperienced drivers drove in a simulator under low- and high-stress conditions. Anxiety was manipulated by competition, the presence of an evaluator, external video camera, and traffic noise. Most drivers showed greater anxiety scores and higher mean heart rates following manipulation. In both groups increased state anxiety decreased car speed control and caused more collisions, accompanied by fewer fixations of longer duration towards the driving lane across a horizontally narrower region. Inexperienced drivers increased the number of short fixations towards cars, while experienced drivers increased the number of short fixations on the speedometer. Although anxiety impairs processing efficiency and performance effectiveness for both groups, attentional changes differ as a function of experience. Inexperienced drivers tended to shift attention to threatening stimuli, while experienced drives were more likely to consciously monitor task goal.

Keywords: anxiety, driving experience, gaze, attentional control theory.

2.1. Introduction

The often-detrimental effects of anxiety on performance have been investigated for a long time. However, recent advances in gaze-tracking technology during action have recently renewed interest in how attention modulates the performance decrements following an increase in anxiety in dynamic situations such as sports, policing, and car driving (ALLSOP; GRAY, 2014; BRIGGS et al., 2011a; CAUSER et al., 2011; MALHOTRA et al., 2014; NAVARRO et al., 2012, 2013; NIBBELING et al., 2012; NIEUWENHUYS et al., 2015; PIJPERS et al., 2005; VICKERS; WILLIAMS, 2007; WILLIAMS et al., 2002). Typically, anxiety can be understood as a (transitory) state or a personality trait. According to Eysenck, state anxiety is an aversive transitory emotional and motivational state evoked by threatening and/or stressful circumstances, while trait anxiety is an individual's propensity towards anxiety. It has been shown that increased levels of state anxiety can disrupt performance by enhancing a performer's propensity for distraction (ALLSOP; GRAY, 2014; JANELLE et al., 1999; WILSON; WOOD et al., 2009), attentional narrowing (BRIGGS et al., 2011a; JANELLE et al., 1999), and/or reduced processing efficiency (BEHAN; WILSON, 2008; CAUSER et al., 2014; NIBBELING et al., 2012; WILSON; VINE et al., 2009).

Recently, Nieuwenhuys and Oudejans proposed an integrated model that encompasses anxiety and perceptual-motor performance for explaining the disparate behavioural responses observed under threatening and stressful circumstances (NIEUWENHUYS; OUDEJANS, 2012, 2017). This model builds heavily on Attentional Control Theory (ACT) (EYSENCK; DERAKSHAN et al., 2007) that is suitable for cognitive tasks, yet extends it to fit the specific characteristics of perceptual-motor performance, including the critical role of visual attention. According to the integrated model, and in line with ACT, increased anxiety provokes performance decrements because it impairs attentional control; it intensifies the engagement of the stimulus-driven system at the expense of the involvement of the goal-directed system. The goal-directed system regulates the conscious control of attention. This top-down system directs attention in accordance with a performer's expectations, knowledge, and current task goals. The stimulus-driven system recruits attentional resources via automatic processing. This bottom-up system serves to detect maximally salient and/or threatening stimuli in the environment. In low stressful situations, the contributions of two attentional systems are optimally coordinated for achieving the task goal. However, with increased levels of anxiety, the systems' coordination is disrupted. Attentional control may shift more to the stimulus-driven system, increasing attention to conspicuous stimuli (ALLSOP; GRAY, 2014; BRIGGS et al., 2011a; EYSENCK; DERAKSHAN et al., 2007; JANELLE et al., 1999; NIBBELING et al., 2012) and away from the goal-directed system. To counter this and with increased mental effort, one may manage to maintain goal-directed attention; in that case, performance is maintained but with decreased processing efficiency (MASTERS; MAXWELL, 2008). On the other hand, if there is indeed a shift toward the stimulus-driven system under high anxiety then the time visually fixating irrelevant/threatening cues is increased (ALLSOP; GRAY, 2014; WILLIAMS; ELLIOTT, 1999) and the number of fixations towards relevant areas of the visual scene is reduced (ALLSOP; GRAY, 2014), leading to hampered performance. In addition, it provokes a relatively narrow range of visual scanning (BRIGGS et al., 2011a). However, it is

not particularly clear whether, and if so to what degree, the effects of increased anxiety differ as a function of the level of experience or expertise.

In car driving—the task under study here—the level of experience (or perhaps expertise) does influence perceptual and motor performance (CRUNDALL; UNDERWOOD, 1998; UNDERWOOD, 2007). For example, inexperienced drivers have been shown to have a reduced visual exploration (e.g., less fixations with a relatively narrower distribution) compared to experienced drivers, particularly when potential hazards are more likely to occur (e.g., driving in dual carriageway, night, and rain visibility). The less developed capacity to acquire information (CRUNDALL et al., 1999; CRUNDALL; UNDERWOOD, 1998; KONSTANTOPOULOS et al., 2010; MOURANT; ROCKWELL, 1972) goes together with an enhanced susceptibility for getting involved in traffic accidents in the first years after obtaining a driving license (CLARKE et al., 2005; UNDERWOOD, 2007). Likely, less experienced drivers require stronger conscious monitoring and control of their driving skills, whereas the experienced drivers' skills proceed more automatically (BROWN; CARR, 1989; FITTS; POSNER, 1967). Less experienced drivers would thus require more processing resources to assure safe driving. Yet, there is a dearth of studies examining whether, and if so how, anxiety mediates these experience-related attentional differences.

From the perspective of the integrated model of Nieuwenhuys and Oudejans (NIEUWENHUYS; OUDEJANS, 2012, 2017), we can predict increased processing demands and/or increased attention for conscious/threatening stimuli. Increased levels of anxiety can cause a reduction in processing efficiency, that is, more attentional resources are consumed to monitor and control the skill (which, for instance, may be reflected in more or longer fixation to task-relevant information such as direction of heading, or speedometer). If auxiliary attentional resources are available to compensate anxiety decrements, performance effectiveness can be maintained under pressure, but at the cost of reduced processing efficiency (EYSENCK; DERAKSHAN et al., 2007; NIBBELING et al., 2012; WILLIAMS; ELLIOTT, 1999). Among inexperienced drivers, for whom driving already is more effortful than for experienced ones, the attentional capacity limits may be more likely to be exceeded (NIBBELING et al., 2012), thus resulting in larger drops in performance effectiveness compared to more experienced drivers (NIBBELING et al., 2012; WILLIAMS; ELLIOTT, 1999). Alternatively, novice drivers may be more easily distracted by conspicuous or threatening stimuli and thus at increased risk of unsafe driving performance (i.e., which, for instance, may be reflected in more or longer fixations for threatening stimuli such as toward other cars to avoid collision).

In traffic, personal factors, such as work-related stress or fatigue, hurry, adverse life events, and/or environmental factors such as a gridlock, an overload of auditory or visual noise can induce increased levels of anxiety and thus affect driver's performance. In this respect, it has been reported that increased anxiety causes deterioration in motor performance (ALLSOP; GRAY, 2014; BRIGGS et al., 2011b) and is related to more frequent involvement in traffic accidents (CLAPP et al., 2011; DULA et al., 2010; ROIDL et al., 2014). A better understanding of how attentional control mediates the relation between anxiety and driving performance can be a first step in further improving the safety of cars and the traffic environment to reduce the adverse effects of increased anxiety. For example, if anxious drivers would indeed be more

easily distracted by conspicuous stimuli, then it is important to take this into account in the design of a car's dashboard or permitting advertisements.

The aim of this study was to investigate whether, and if so how, adverse effects of anxiety on perception and action in drivers are modulated by driving experience. In line with previous findings (ALLSOP; GRAY, 2014; BRIGGS et al., 2011a; EYSENCK; DERAKSHAN et al., 2007; MURRAY; JANELLE, 2003; NIBBELING et al., 2012; WILLIAMS; ELLIOTT, 1999), it was hypothesized that high levels of state anxiety would shift drivers' attention from task-relevant stimuli toward threat-related and/or salient stimuli. We suspect that the particular shift in balance between the two attentional systems may depend on the available attention resources. Accordingly, because they need fewer resources for regular driving, experienced drivers may more likely maintain the contribution of the goal-directed systems and thus attention for stimuli that inform about heading and speed (e.g., fixations toward the lane, speedometer). On the other hand, inexperienced drivers may be more easily distracted by conspicuous and/or threatening stimuli that inform about collisions (e.g., more fixations toward hard shoulder, other cars, rearview mirror) and would thus show a drop in performance effectiveness (e.g., less car speed control or more occurrences of collisions), due to non-automatized steering control which makes this group unable to allocate sufficient resources to minimize anxiety decrements.

2.2. Method

Participants

Forty drivers (25 male, 15 female) voluntarily participated in this experiment and filled out the Driving Experience Questionnaire, which was developed by the experimenters to quantify the drivers' experience, prior to participation. This questionnaire consisted of three items for gauging the frequency of driving in the city (Q1: *'How long have you been driving a car weekly?'*; Q2: *'How many days a week are you typically driving a car?'*; Q3: *'How many kilometres are you typically driving per day?'*), and two items about the frequency of driving on the highway (Q4: '*Monthly, how often have you been driving a car on the highway?'*; Q5: *'How many kilometres are you typically driving during such a trip?*'). To quantify the driving experience (D_e) of the drivers, experience in the city was summed with the experience on the highway using the following equation:

$$D_e = [((Q2 * 4) * 12 * Q1 * Q3) + (Q4 * Q5)] \quad (3)$$

where Q2 is the weekly driving rate in the city and was used to calculate the annual driving rate in the city [(Q2*4) *12]. To estimate the total rate of driving in the city, the annual driving rate was multiplied by the number of years of the driving license (Q1), which was multiplied by the number of kilometres travelled per day (Q3). To estimate the total rate of driving on the highway, the monthly driving rate on the highway (Q4) was multiplied by the total number of kilometres in each trip (Q5).

Drivers were classified into an inexperienced group (n = 20), when DE was less than 5000 kilometres, and an experienced group (n = 20), when DE was above 30,000 kilometres (LEHTONEN et al., 2014; SUMMALA et al., 1996). Both groups were asked to perform a

simulated driving task in a low- and high-stress condition. Drivers' self-reported anxiety scores were compared prior and immediately after each condition and used as inclusion criteria. Four experienced and nine novice drivers did not report increased anxiety in the high-stress condition compared to the low-stress condition. Because it was not particularly clear how these participants coped with the high-stress condition (i.e., they did not have lower trait anxiety scores), they were excluded from further analyses.

The remaining sixteen experienced drivers (26.38 ± 2.80 years old; 83.38 ± 17.89 kg; 177 ± 0.08 cm; 154228.44 ± 25190.37 km) and eleven inexperienced drivers (24.00 ± 2.66 years old; 66.09 ± 10.79 kg; 169 ± 0.09 cm; 1830.00 ± 694.05 km) were included for data analyses. To check whether experienced and inexperienced participants showed no difference in tendency to respond to stressful circumstances with a higher level of state anxiety, the Brazilian Portuguese version of the Trait scale of the short-form State-Trait Anxiety Inventory (STAI-T) (FIORAVANTI-BASTOS et al., 2011) was also completed prior to participation. Student's t-test revealed that there was no significant difference between groups for the trait-anxiety score, t (2) = -1.831, p = .079 (experienced drivers = 10.44 ± 2.25 pts; inexperienced drivers = 12.09 ± 2.38 pts). To assess the visual acuity of the participants the Snellen test was conducted, which consists of reading letters from large to small with one eye at a time. One printed page with the test (A4 standard format) was placed at 6 meters away from the individuals' eyes. The test was performed with visual acuity corrections (e.g., contact lenses or glasses) when necessary. As inclusion criteria were selected those who obtained visual scores were between 20/20 and 20/30. Ethical approval for the study was obtained from the Local Committee and participants signed informed consent before the start of the study.

Apparatus

The simulated driving task was performed with City Car Driving simulator (Forward Development, version 1.5) that was configured to drive on a highway (multi-lane, 20% of traffic and daytime visibility) with a left-handed vehicle of a manual gearbox. The simulation was run using a PC (ASUS), running Windows 7 Ultimate Edition Service Pack 1, connected to a TV screen (LG, LED 46"). To approach a realistic condition, the TV screen was fixed in a cockpit (XT Premium V2 Racing Extreme) with the driver's seat positioned 100 cm away from the screen. In addition, driving accessories (steering wheel, pedals, and gearbox - Logitech, G27) were attached to the cockpit to control the vehicle during the driving task and configured with Logitech Gaming Software (version 5.10.127). Drivers' eye movements were recorded using Head-Mounted Eye Tracker (model H6, Applied Science Laboratory, USA) at a sampling rate of 60 Hz. This video-based analysis system of eye movements contains two micro-cameras, one that films the eye and another one the scene, attached to a headgear that was anatomically adjusted to the participant's head. In the eye video, pupil and corneal reflection centroids were identified and the vector between both is used to determine horizontal and vertical coordinates of eye position on scene video.

Participants' anxiety was determined using psychological and physiological measures. The Brazilian Portuguese version of State scale of the short-form State-Trait Anxiety Inventory (STAI-S) (FIORAVANTI-BASTOS et al., 2011) was used to measure state anxiety. The short-form STAI-S is a 6-item questionnaire about an individual's current psychological state, which encompasses positive items (e.g., *"I feel calm", "I feel content"*) and negative items (e.g., *"I*

am tensed", *"I am worried"*). Participants rated each item on a 4-point Likert scale from *"Not at all"* to *"Very much"*. Scores from positive items were inverted for their opposite value (e.g., score 1 is inverted in 4; score 2 is inverted in 3) and the scores from negative items were maintained at the original value (MARTEAU; BEKKER, 1992). The scores from each item were summed to determine the level of anxiety, considering that higher scores represent a greater state anxiety. The short-form STAI-S was completed by all participants prior to and immediately after performing in the low- and high-stress conditions. Heart rate was measured using the Polar (RS800CX) (40), which contains an electrode belt and transmitter (WIND). The transmitter recorded and processed the HR records as beats per minute (bpm) at a frequency of 100 Hz.

Procedure

Prior to the start of the test, participants had their rest HR measured. The electrode belt (Polar) was strapped around the participants' chest, with the transmitter placed ventrally to register the HR during the experiment. After that, participants were asked to take a seat in the cockpit and the gaze tracker's headgear was adjusted on their head. A nine-point calibration plan was projected on the TV screen, for which participants were asked to maintain their head as still as possible and to move their gaze from one point to another in ascending order. After calibration participants were informed that the simulated driving task consisted of uninterrupted driving during three minutes on a highway. Furthermore, participants were instructed to maintain car speed between 100 and 120 km/h and to avoid traffic violations (e.g., no turn signals in overtaking, collisions). The anxiety manipulation (see below) was provided a few minutes before the beginning of the high-stress condition. Participants had three minutes to familiarize themselves with the simulator and equipment. Trial time started to be timed when drivers reached 100 km/h for the first time, and recordings of gaze fixations and HR were started synchronously.

Anxiety manipulation

The simulated driving task was performed in two experimental conditions: i) low-stress, driving task performed in a quiet environment; ii) high-stress, driving task performed in a competitive environment, ego-threatening instructions, performance evaluation, external video camera and traffic noises. The competition consisted of performing the simulated driving task by making as few errors as possible and less than other competitors. Driving errors were defined as the time that drivers achieved speeds outside the speed bandwidth (i.e., < 100 km/h or > 120 km/h), the absence of the turn signals when overtaking, and/or collisions. For the competition, these errors were scored as one, one, and three errors, respectively. An evaluator positioned behind the cockpit during the high-stress condition determined the errors instantly. First, participants were informed about the competition rules and the presence of the evaluator and, subsequently, that the winner of the competition would win a Tablet (Galaxy SMMM-T113NU, Samsung). Second, the ego-threating instructions were that the performance during simulated driving task would represent their real driving abilities, and thus, at the end of the study a performance ranking would be disclosed among participants. Third, an external video camera (Sony, DCR SR68) was placed in front of participants in order to register their arms movements in steering wheel control. They were informed that, in the case of a tie in the

competition, the analyses of their arm movements would be used to indicate who the best driver was. Finally, a computer laptop (Lenovo, G450) running Windows Media Player (Windows 10) and connected to an amplifier box (Meteoro, 50W) was used to reproduce traffic noises at a volume between 70 and 80 db. Performance feedback to the participants was only provided after the test was completed. This revealed which errors they had committed under high-anxiety and, after summing all errors, their respective position in the performance ranking. The choice for these four manipulations was based on previous research, in which they have proven successful in increasing participants' experience of (transitory) anxiety and are associated with decrements in performance efficiency and/or outcome (BAUMEISTER; SHOWERS, 1986).

Data Analysis

In order to verify the anxiety manipulation, a total score of the short-form STAI-S before and immediately after each experimental condition was calculated. Heart rate data (bpm) was transmitted at the end of each recording to a PC computer (ASUS) via a bidirectional infrared interface using the Polar® software (Protrainer 5).

Driving performance was assessed via frame-by-frame video analysis to calculate the percentage of the trial time driving outside of the speed zone and the frequency of collisions in each trial. The percentage of trial time driving outside of speed zone was defined as the duration (s) at which the car speed was below or above the specified speed zone divided by total trial time and multiplied by 100. Finally, the total number of collisions throughout driving performance was counted for each participant in both conditions.

Gaze recordings were transferred to a PC (ASUS) running ASL Results Plus software (version 1.8.2.18, Applied Science Laboratory, USA) for further analysis with Areas of Interest (AOIs). AOIs are two-dimensional (2-D) regions defined in the viewing plane (e.g., scene video from Eye Tracker) that allow the calculation of the gaze behaviour (number and duration of fixations) in relevant parts of the visual scene. Four AOIs were considered as sources that contain potentially relevant and/or threatening information to performing the task: i) lane, which provides the essential visual information to steering control; ii) other cars, which need to be avoided and iii) speedometer, task-relevant information for successful task performance; iv) rearview mirrors, task-relevant information for deciding overtakes. Total number (unit) and mean duration (ms) of fixations to each AOI were calculated. Fixation detection criteria were a minimal duration of 100 milliseconds and the spatial limit of 1 degree (LAND, 2006).

Furthermore, the horizontal and vertical variance of fixation locations (cm) was calculated to express the range of visual scanning strategy employed by drivers in the conditions (CRUNDALL et al., 1999; CRUNDALL; UNDERWOOD, 2011). Horizontal and vertical of fixations position were exported as text files in a matrix of two columns (horizontal and vertical eye position, respectively) by the number of rows equivalent to the number of fixations in each trial. Then, the square root of standard deviations of the fixations position in both axes was calculated using MATLAB (MATHWORKS, 7.10.0.499).

Statistical Analysis

To investigate the effects of experience and anxiety on gaze behaviour and performance of drivers, group (experienced, inexperienced) by condition (low-stress, high-stress) ANOVAs with repeated measures on the last factor were performed on the following dependent variables:

anxiety - i and ii) total score STAI-S and mean Heart Rate (HR); performance - iii and iv) % time driving outside of the speed zone and number of collisions; gaze behaviour - v and vi) total number and mean duration of fixations on lane; vii and viii) total number and mean duration of fixations on cars; ix and x) total number and mean duration of fixations on speedometer; xi and xii) total number and mean duration of fixations on rearview mirrors; xiii and xiv) horizontal and vertical variance of fixations; Statistical analyses were run using SPSS Statistics (17.0.1). Tukey Honestly Significant Difference tests, Greenhouse-Geisser degrees of freedom adjustments, and Bonferroni multiple-comparison probability adjustments were conducted in all statistical analyses as necessary. The value alpha was .05. Effect sizes were calculated using Partial Eta Squared with 0.02 or less, 0.13, and 0.26 or more, representing small, medium and large effect sizes, respectively (COHEN, 1988).

2.3. Results

Manipulation check for anxiety

A complete overview of means and SDs of the anxiety measures is provided in Table 1. For the STAI-S and HR the ANOVAs revealed a main effect for condition, $F(1,25) = 80.590$, $p < .001$, $\eta_p^2 = .763$ and $F(1,25) = 35.917$, $p < .001$, $\eta_p^2 = .763$ respectively, indicating that drivers self-reported more anxiety during the high-stress than the low-stress condition, and that they had higher HRs during the high-stress than the low-stress condition. For both STAI-S and HR there were neither differences between groups, $F(1,25) = .334$, $p = .568$, $\eta_p^2 = .013$ and $F(1,25) = .111$, $p = .742$, $\eta_p^2 = .004$, nor any interactions, $F(1,25) = .212$, $p = .649$, $\eta_p^2 = .008$ and $F(1,25) = .640$, $p = .431$, $\eta_p^2 = .025$, respectively.

Table 1. Means (SDs) for the manipulation check during simulated driving task in low- and high-stress conditions.

	Experienced drivers		Inexperienced drivers	
	Low-stress	High-stress	Low-stress	High-stress
STAI-S score (6-20)	9.75 (1.98)	13.69 (2.82)	9.00 (3.25)	13.36 (2.58)
Heart rate (bpm)	79.34 (10.16)	92.92 (14.31)	79.52 (10.81)	89.9011.92)

Performance

For the % time driving outside of the speed zone (Figure 7a) and the number of collisions (Figure 7b) the ANOVAs revealed a main effect for condition, $F(1,25) = 15.115$, $p = .001$, $\eta_p^2 = .377$ and $F(1,25) = 14.224$, $p = .001$, $\eta_p^2 = .363$, respectively, showing that in the high-stress condition drivers increased both the time driving outside the speed zone and were involved in more collisions compared to the low-stress condition. For both the time driving outside of the speed zone and the number of collisions there were no differences between groups, $F(1,25) = 2.980$, $p = .097$, $\eta_p^2 = .106$ and $F(1,25) = .042$, $p = .839$, $\eta_p^2 = .002$, or interactions, $F(1,25) = 2.289$, $p = .143$, $\eta_p^2 = .084$ and $F(1,25) = .355$, $p = .557$, $\eta_p^2 = .014$, respectively.

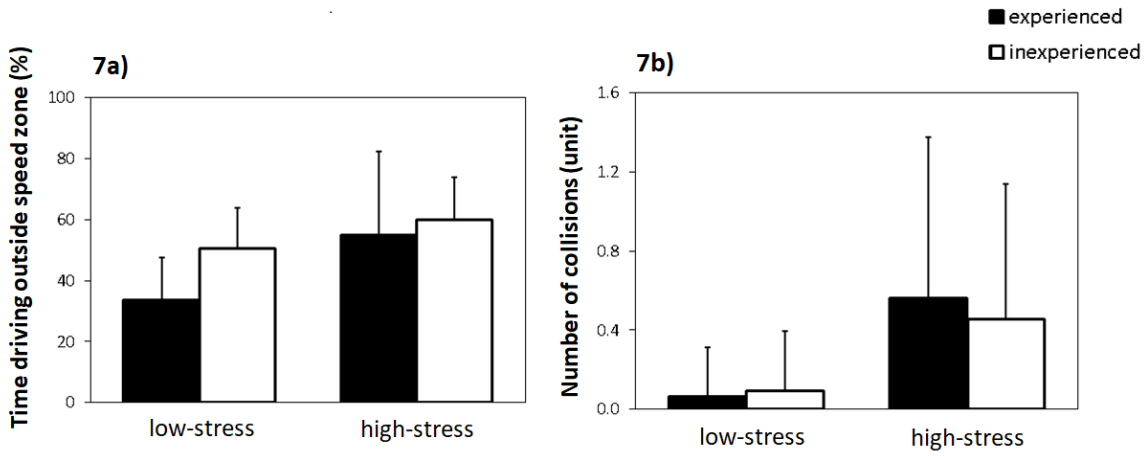


Figure 7: Percentage of the trial time driving outside of speed zone (a) and the number of collisions (b) as a function of experience and stress.

Gaze behavior

Means and SDs of the gaze behavior are provided in Table 2.

Areas of Interest analyses

For the total number and mean duration of fixations on the lane the ANOVA revealed a main effect for condition, F (1,25) = 16.855, p = .000, η_p^2 = .403 and F (1,25) = 3.904, p = .053, η_p^2 = .135, respectively. Drivers performed fewer fixations, yet of longer duration on lane in the high-stress than in the low-stress condition. There were no significant differences for group, F (1,25) = 2.434, p = .131, η_p^2 = .089 and F (1,25) = .066, p = .800, η_p^2 = .003, or interaction between group and condition, F (1,25) = 1.319, p = .262, η_p^2 = .050 and F (1,25) = .443, p = .512, η_p^2 = .017, respectively.

For the total number of fixations on rearview mirrors the ANOVA revealed a main effect for condition, F (1,25) = 7.790, p = .010, η_p^2 = .238, but no differences for group, F (1,25) = 2.200, p = .150, η_p^2 = .081, or the interaction, F (1,25) = .138, p = .714, η_p^2 = .005. In the high-stress condition, the drivers decreased the total number of fixations on the mirror compared to the low-stress condition. For the mean duration of fixations on rearview mirror there were no significant differences for condition, F (1,25) = 1.524, p = .228, η_p^2 = .057, group, F (1,25) = .934, p = .343, η_p^2 = .036, or their interaction, F (1,25) = 1.023, p = .322, η_p^2 = .039.

For the total number and mean duration of fixations on cars the ANOVAs revealed main effects for condition, F (1,25) = 7.953, p = .009, η_p^2 = .241 and F (1,25) = 12.507, p = .002, η_p^2 = .333, respectively, but no main effects for group, F (1,25) = 4.024, p = .066, η_p^2 = .109. Yet, the main effects for condition were superseded by interactions with group, F (1,25) = 6.789, p = .015, η_p^2 = .214 and F (1,25) = 14.211, p = .001, η_p^2 = .362, respectively. *Post-hoc* pair-wise comparisons indicated that only inexperienced drivers increased the total number of fixations on cars, which were of shorter duration, during the high-stress condition compared to the low-stress condition. The experienced drivers showed no significant differences in gaze behavior toward other cars as function of anxiety.

The total number of fixations on the speedometer the ANOVA revealed a main effect for group, F (1,25) = 4.284, p = .049, η_p^2 = .146, as well as and interaction between group and condition, F (1,25) = 12.834, p = .001, η_p^2 = .339. Also, for the mean duration of fixations on the speedometer a main effect for condition, F (1,25) = 36.437, p = .000, η_p^2 = .593, for group, F (1,25) = 9.293, p = .005, η_p^2 = .271, and an interaction between both factors, F (1,25) = 5.050, p = .034, η_p^2 = .168, were revealed. Post-hoc tests indicated that in the high-stress condition only experienced drivers increased the number of fixations to the speedometer, yet these were of shorter duration compared to the low-stress condition. The inexperienced drivers showed no such differences.

Variance of fixation location

For the horizontal variance, the ANOVA revealed a main effect for condition, F (1,25) = 11.534, p = .002, η_p^2 = .316, but no significant difference for group, F (1,25) = .254, p = .618, η_p^2 = .010, or the interaction between group and condition, F (1,25) = .200, p = .659, η_p^2 = .008. The main effect showed that drivers reduced the horizontal variance of fixations under high-stress condition compared to low-stress condition. For the vertical variance of fixations, the ANOVA showed neither effects for condition, F (1,25) = .486, p = .492, η_p^2 = .019, nor for group, F (1,25) = 1.957, p = .174, η_p^2 = .073, and the interaction between the two factors, F (1,25) = .352, p = .558, η_p^2 = .014.

Table 2. Means (SDs) for the gaze behavior of each group during simulated driving task in low- and high-stress conditions.

	Experienced drivers		Inexperienced drivers	
	Low-stress	High-stress	Low-stress	High-stress
Lane				
Total number of fixations	139.81 (41.68)	113.00 (39.88)	125.27 (63.58)	77.64 (44.48)
Mean fixations duration (ms)	471.75 (72.00)	495.06 (103.29)	469.00 (108.65)	516.00 (125.22)
Cars				
Total number of fixations	138.37 (29.59)	139.69 (24.58)	143.55 (34.57)	176.73 (37.56)
Mean fixations duration (ms)	480.56 (85.26)	483.75 (83.65)	583.27 (103.70)	483.45 (79.15)
Speedometer				
Total number of fixations	64.50 (30.74)	86.12 (48.75)	51.36 (23.92)	44.45 (25.98)
Mean fixations duration (ms)	367.88 (73.20)	312.63 (53.57)	288.18 (44.10)	262.91 (42.96)
Rearview mirrors				
Total number of fixations	39.25 (18.81)	24.88 (14.73)	46.73 (22.83)	35.73 (23.22)
Mean fixations duration (ms)	545.31 (176.54)	460.25 (206.32)	565.18 (171.15)	556.73 (158.02)
Variance of fixations location				
Horizontal (cm)	132.50 (60.94)	94.19 (58.56)	148.26 (77.96)	98.34 (37.34)
Vertical (cm)	72.64 (23.58)	71.80 (30.26)	91.82 (44.59)	81.3737.15)

2.4. Discussion

The aim of this study was to investigate the effects of anxiety on gaze behavior and performance of car drivers and how this is mediated by experience. Inexperienced and experienced drivers were invited to drive in a simulator within a certain speed zone and without making collisions. Competition with ego-threatening instructions and the presence of an evaluator were used to increase anxiety (ALLSOP; GRAY, 2014; BEHAN; WILSON, 2008; BRIGGS et al., 2011). Increases in STAI-S scores and mean heart rate in the high-stress condition compared to low-stress condition in both skill groups confirmed that the manipulations were successful (i.e., participants who did not show increased anxiety were excluded from analyses). The increased anxiety evoked significant disruptions in driving performance for both groups of drivers. In comparison to low-stress condition, drivers with increased anxiety spent more time driving outside the speed zone (100 – 120 km/h) and showed an increased collision rate. As this was true for both groups, apparently despite their experience and more automatic behavior, even experienced drivers did not, contrary to the expectations, have sufficient resources to maintain attentional control and thus performance.

We were especially interested to find out to what degree these performance decrements could be associated with deterioration in attentional control (as measured by shifting patterns of gaze) as would be predicted based on the integrated model of anxiety and perceptual motor performance (NIEUWENHUYS; OUDEJANS, 2012, 2017). We addressed whether, and if so how, increased anxiety would affect attentional control differently as a function of a driver's experience. The shifts in attention control following increased anxiety showed not only similarities but also differences between the two groups, despite the performance decrements being of similar kind. Specifically, the experienced drivers showed an increased number of shorter fixations towards the speedometer with increased anxiety, while the inexperienced group showed an increased number of shorter fixations towards other cars. Other shifts in visual attention due to increased anxiety were similar across groups: participants showed fewer fixations toward the lane and rearview mirrors. Although these fixations tended to be longer, overall fixation duration decreased.

In line with the Integrated Model (ALLSOP; GRAY, 2014; BRIGGS et al., 2011; JANELLE et al., 1999; NIBBELING et al., 2012), the attentional shifting towards threat-related stimuli (other cars – potential collisions) among inexperienced drivers may be interpreted as a consequence of a larger role of the stimulus-driven attentional system and reduction of the goal-directed system (i.e., shift of attention from more task-relevant to more threatening stimuli). This result partly confirms our hypothesis that inexperienced drivers would be more affected by anxiety manipulation than their experienced counterparts. NIBBELING; OUDEJANS; DAANEN (2012) observed that in a dart throwing task both dart players (experts) and undergraduate students (inexperienced group) showed reduced final fixation durations on bulls-eye under high-stress conditions (i.e., high on a climbing wall) compared to the low-stress conditions (i.e., low on the climbing wall); however, only the students showed a decrease in performance accuracy as the final fixation duration dropped from over a second to below 650 ms, which was apparently no longer sufficient to maintain performance. Thus, novice performers were less capable to allocate sufficient attentional resources to minimize anxiety decrements on performance. Furthermore, WILLIAMS; ELLIOTT (1999) showed that expert and novice karate practitioners, in response to videotaped

offensive sequences under low-stress (i.e., in neutral performance instructions) and high-stress (i.e., in competition and ego stressors instructions) conditions, had a better performance accuracy with increased anxiety; however, only novices increased the number of fixations towards opponents' hands and legs (i.e., sources of potential threat) while the expert group maintained their attentional allocation to the central area of the opponent (WILLIAMS; ELLIOTT, 1999).

According to the integrated model of anxiety and perceptual motor performance (NIEUWENHUYS; OUDEJANS, 2012, 2017), increased anxiety requires extra processing resources required to inhibit attention shifts toward threat/distractors. Accordingly, the performance decrements along with a shift towards fixation cars (i.e., potential threat) among the less experienced performers appear a consequence of insufficient mental resources to resist interference from threatening distractors (ALLSOP; GRAY, 2014; EYSENCK et al., 2007; JANELLE et al., 1999). There is ample evidence to show that direction of gaze determines the direction of heading in the environment (LAND, 2006; LAND; HAYHOE, 2001). Accordingly, increased looking at other cars likely results in a stronger inclination to steer toward other cars. By contrast, the performance decrement following the increase in anxiety among experienced drivers was associated by increased monitoring of the speedometer to adhere to speed instructions, rather than attention shift toward threatening stimuli. It seems that with increased anxiety, experienced drivers' attention was shifted toward task-relevant information, arguably to (more) consciously monitor speed. This may reflect a stronger contribution of the goal-directed system with increased anxiety. Apparently, neither the changes in attention of the experienced drivers, nor those of the inexperienced drivers were fully effective in preventing the negative effects of anxiety as performance of both groups decreased with anxiety. NIEUWENHUYS; OUDEJANS (2012, 2017) argue that skill-focused attention (i.e., explicitly monitoring own performances) may be a specific form of distraction for expert performers, as they no longer need this kind of attention (i.e., skilled performance is typically automatized). The increased number of fixations toward the speedometer (i.e., to monitor speed) may reflect such (debilitative) skill-focused distraction. The short duration of these fixations might underline the inefficiency of this shift in goal-directed attention. Paradoxically, the enhanced monitoring of performance may have resulted in reduced performance because of an increased effort occurs for maintaining performance level (ENGLERT; OUDEJANS, 2014).

Limitations of the Research

Four experienced and nine novice drivers were excluded from data analyses because they did not show increased anxiety score. It is not particularly clear why the stress manipulation did not inflict an increase in experienced anxiety in these participants. They did not report higher trait anxiety. Perhaps they were more familiarized with competitive environments and driving simulations (e.g., by playing racing video games in a competitive mode) and/or they were less compelled to perform well in the competition. Because it remained uncertain how these participants coped with the high-stress condition, it is inappropriate to use them as a control group, and hence, they were excluded from further analyses. However, this does raise the issue of the representativeness of the stress manipulations. Possibly, rather than introducing a competitive element, stress manipulations such as tailgating, speeding and aggressive driving

in the simulation may result in more systematic increases in state anxiety. Such may also represent a clearer, unequivocal definition of threat-related information (and distinction from target-related information), allowing stronger tests of the nature of the attentional shifts predicted by the integrated model and ACT. Nonetheless, it is important to realize for future research that determination and interpretation of areas of interest for gaze will need to be task- and stressor-specific.

Conclusion

In sum, increased anxiety led to drops in performance for both inexperienced and experienced drivers. Yet, the underlying attentional mechanisms showed important differences, along with similarities. With anxiety inexperienced drivers showed an attentional shift from task-relevant to threat-related information (i.e., other cars), while experienced drivers shifted their attention more to task-relevant information (i.e., the speedometer), possibly to increase conscious monitoring of performance. Thus, we may conclude that effects of anxiety on attentional control and performance are mediated by the level of expertise.

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Chapter 3.

Combining experiences of race gaming and natural driving affects gaze location strategy in simulated context

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Abstract

The aims of the study were to investigate the effects of race gaming experience in playing racing video games on gaze behaviour and performance of drivers and the effects of natural driving experience on gaze behaviour and performance of gamers. Thirty participants, divided into drivers-gamers, drivers-non-gamers and non-drivers-gamers, were asked to drive in a race circuit as fast as possible while their eye movements were recorded. Drivers-gamers spent more time looking to the lane than non-drivers-gamers. Furthermore, drivers-gamers performed greater number of fixations towards the speedometer and showed faster performance in the racing task than the drivers-non-gamers. Combining natural driving and race gaming experiences changes the gaze location strategy of drivers.

Keywords: racing video games; ergonomics; visual search; virtual environment

3.1. Introduction

Playing action video games modifies visual attention and oculomotor performance. Video game players have shown faster reaction time to detect peripheral targets and faster stimulus-response mapping in both easy and difficult visual search tasks (CASTEL et al., 2005; DYE et al., 2009), better performance in ignoring distractors and an improved attentional switching ability (GREEN; BAVELIER, 2003, 2007), as well as an enhanced visual short-term memory (MCDERMOTT et al., 2014) than non-video game players. In addition, experienced gamers also have demonstrated shorter saccadic reaction time and higher saccadic peak velocities than non-gamers (MACK; ILG, 2014; WEST et al., 2013).

In the last decade, growth in video game usage has been observed worldwide. In Brazil, 56 million people regularly use video games as their favourite pastime; racing games appear as a very popular game type (IBOPE, n.d.). This broad interest can be due to the fact that these games offer realistic interactions for their players, simulating highly complex traffic scenarios, what would represent the visual experience of drivers in the natural, out-of-laboratory world (BEULLENS et al., 2011; CICERI; RUSCIO, 2014). Pre-drivers, such as pedestrians and cyclists, are particularly active street users that intend to become drivers (GATERSLEBEN; HADDAD, 2010) and possibly interact with complex traffic environments through driving simulators and racing video games. However, there is a relationship between video game playing and adolescents' attitudes and intentions to exhibit risky driving behaviour in the future (BEULLENS et al., 2011). Thus, the impact of playing video games on perceptual and motor performance of both drivers and pre-drivers (typically racing video gamers) has been a research topic in focus in human factors scientific field.

Recent studies with virtual environment (i.e., action video games, simulators, and virtual reality) have emerged as an alternative approach to study and understand skilled performance in sports (CRAIG, 2014; NEUMANN et al., 2017), physical rehabilitation programs for vulnerable populations such as patients with Parkinson's disease and cerebral palsy (HOWARD, 2017), and motor learning process (PASCO, 2013). Particularly, drivers in their earliest years of driving license are more susceptible to be involved in traffic accidents (CLARKE et al., 2005); gaze behaviour analyses have showed crucial differences between experienced and novice drivers (UNDERWOOD et al., 2003, 2007). According to the World Health Organization, about 1.25 million people die by traffic accident and between 20 to 50 million victims become disabled by non-fatal crashes each year worldwide (WORLD HEALTH ORGANIZATION, 2016). The Institute of Applied Economic Research of Brazil (IPEA) recently revealed that all traffic accidents in 2014 had a total cost for Brazilian Government estimated in R$ 40 billion (INSTITUTO DE PESQUISA ECONÔMICA APLICADA, 2015). These economic losses are consequences of high costs in rehabilitation treatments, reduction of the labour productivity, investigation of accident causes, and others, and represent a serious issue of Public Health and Economic Management that needs to be attenuated.

Driving experience plays a critical role in driving. It has been shown that experienced drivers perform a greater number of shorter fixations with a wider horizontal spread across the visual scene when compared to the novice ones (CRUNDALL; UNDERWOOD, 1998; KONSTANTOPOULOS et al., 2010), indicating a faster processing time, and, consequently, a superior steering control performance. For this reason, the understanding of driver's learning

process is an important topic in cognitive ergonomics research and a relevant issue to prevent road accidents. CICERI; RUSCIO (2014) recorded eye movements of experienced- and non-drivers (both groups regularly played racing video games) in both natural and simulated scenarios with the same type of road interactions. Drivers-gamers performed fixations more often, with longer durations, towards the relevant portions of the visual scene (i.e., lane, rearview mirrors, and speedometer), and moved their eyes horizontally in a wider spread than non-drivers-gamers. In addition, non-drivers-gamers ignored traffic road signs and potential areas of interactions (e.g., crosswalk and roundabouts) (CICERI; RUSCIO, 2014). The authors suggested that visual search strategy of non-drivers-gamers was poorer and unsafe when compared to drivers-gamers. On the other hand, it is unclear if the specific gaze strategy demonstrated by the drivers-gamers, in comparison with non-drivers-gamers, was influenced by natural driving experience or video game practice.

The aim of this study was to investigate the effects of experience in playing racing video games on gaze behaviour and performance of drivers during a simulated racing task. An additional goal was to determine the effects of experience in driving under natural circumstances on racing gamers' visuomotor performance. It was hypothesized that the most experienced participants, the drivers-gamers, would exhibit a gaze strategy that combines the smallest relative number of fixations, the largest relative fixation durations, mainly directed to the race lane area of interest, and the largest variance of fixations, particularly in the vertical axis, with the smallest total race time as compared to driver-non-gamer and non-drivers-gamers. Differences between drivers-gamers and drivers-non-gamers were expected to represent effects of the experience in playing racing video games while differences between drivers-gamers and non-drivers-gamers were expected to represent effects of the experience due to licensing process and natural driving practice.

3.2. Method

Participants

Thirty young adults voluntarily participated in this experiment and were divided in three experimental groups according to their driving experience in natural and virtual environments. Ten drivers-gamers (DG, 26.6 ± 2.3 years old, 84.6 ± 18.9 kg, 176.9 ± 3.7 cm), with natural, real-world driving experience of at least four years and who regularly play racing video games at the minimum frequency of three times per week with one hour per session; ten drivers-non-gamers (DNG, 29.2 ± 5.0 years old, 68.4 ± 22.4 kg, 166.4 ± 11.6 cm), with natural, real-world driving experience of at least four years and without video game experience in any type of game; and ten non-drivers-gamers (NDG, 20.9 ± 3.8 years old, 65.9 ± 10.7 kg, 168.4 ± 6.9 cm), who intend to become a driver (e.g., pre-drivers, GATERSLEBEN; HADDAD 2010) and regularly play racing video games at the minimum frequency of three times per week with one hour per session. Participants with normal or corrected vision, no sensorimotor and neurological impairment were selected. Ethical approval for the study was obtained from the Local Committee and participants signed informed consent before starting the study.

Apparatus

Eye movements were recorded using Head-mounted Eye Tracker (model H6, Applied Science Laboratory, USA) at a sampling rate of 60 Hz. This video-based analysis system of

eye movements contains two micro-cameras, one film the eye and other record the scene, attached to a headgear that was anatomically adjusted to the participant's head. For the eye video, pupil and corneal reflection centroids were identified and the vector between both of them were used to determine horizontal and vertical coordinates of eye position on scene video. The racing video game Gran Turismo (version 4) was run on PlayStation 2 (SONY) console, and it was projected from multimedia BenQ (MX720) to a screen Projetelas (model Infinity) 204 cm x 154 cm. In order to provide a more realistic driving context to the experimental task, steering wheel and accelerator and brake pedals were used (Logitech model G-27). The steering wheel was attached to a regular table (width = 1.3 cm x depth = 59.5 cm x height = 75 cm) and pedals were set on the floor in front of the participant; distances between the participants and the accessories were individually defined to allow a comfortable driving posture. The racing video game Gran Turismo was configured in Arcade Mode, Time Trial, Original Circuits, Autumn Ring Mini, and Ford Ka'01.

Procedure

Prior to start testing, participants were asked to take a seat and had eye tracker's headgear adjusted on their head. A nine-point calibration plan was projected on the TV screen and participants were asked to maintain their head as still as possible and to move their gaze from one point to another in ascending order. After calibration and prior to data collection, participants had three minutes to familiarize themselves with the racing game software and the experimental apparatus while driving. Furthermore, participants were asked to drive as fast as possible at the race circuit for three laps, without the presence of other cars. This racing task was performed twice for each participant while data were collected.

Data analysis

Gaze recordings were transferred to a PC (ASUS) running ASL Results Plus software (version 1.8.2.18, Applied Science Laboratory, USA) for further analysis with Areas of Interest (AOIs). AOIs were two-dimensional (2-D) regions defined in the viewing plane (e.g., scene video from Eye Tracker) in which the gaze fixation patterns (number and duration of fixations) were identified in relevant parts of the visual scene. The fixation criteria were as follow: fixation onset occurred when two times point of gaze standard deviation (95% confidence interval) was less than one degree of visual angle (horizontal and vertical) over 100 ms (seven data samples); fixation offset occurred when three data samples deviated from initial fixation value by more than one degree of visual angle (horizontal and vertical). Four AOIs were defined (Figure 8): i) race lane, that provided the essential visual information to steering control (Land & Horwood, 1995; Land & Lee, 1994); ii) chronometer, that provided visual feedback about the duration (s) of each lap and the total duration (s) of each participant performance as a sum of the three laps; iii) speedometer, that provided visual feedback of the car speed throughout the trial; iv) outside, all parts of the visual scene that were not included in other AOIs. Considering that each participant completed the driving task in different durations, relative fixations were calculated according to the specific trial duration of each participant; relative number of fixations (r-NUMFIX) in each AOI (unit/min) was calculated by dividing the total number of fixations in each AOI by the total trial time (converted from seconds to minutes). In addition, the relative fixations duration (r-DURFIX) in each AOI (%) were

measured by dividing the total fixation duration in each AOI by the total trial time multiplied by one hundred, expressing the percentage of the total trial time that participants remained with the eyes stationary on each AOI.

Horizontal and vertical variances of fixation locations (pixels) were calculated to express the range of visual scanning strategy employed by drivers (Crundall et al., 1999; Crundall & Underwood, 2011). Horizontal and vertical axes of fixation positions were exported as text files in a matrix of two columns by the number of rows equivalent to the number of fixations found in each trial. The square root of standard deviations of the fixation positions in both axes were calculated using MATLAB (MathWorks, 7.10.0.499). The scene video of the Eye Tracker provided the recording of performance. The total race time (s) was measured for each participant in each trial by summing the race time in each of the three laps.

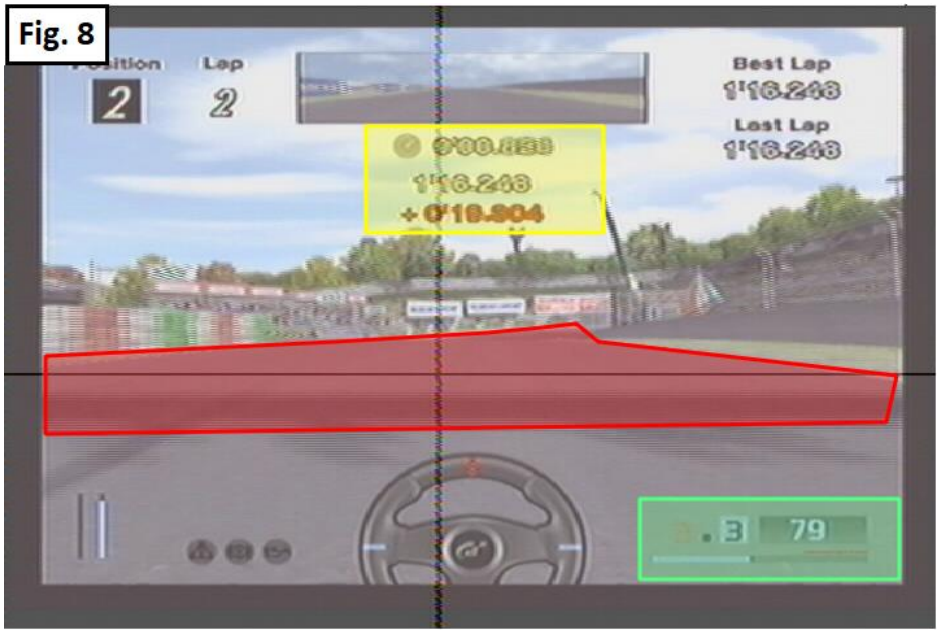


Figure 8: The scene video from Eye Tracker that represents the participant's line of gaze (black cursor). AOIs defined for data analysis: race lane (red), chronometer (yellow), speedometer (green), and outside.

Statistical analysis

In order to specify the contribution of each experience factor of interest such as natural driving and race gaming, the statistical analysis was divided in two tests. Data were tested for effect of driving experience on gaze behaviour in a racing video game environment; dependent variables were submitted to a one-way Analysis of Variance (ANOVA) with group main effect (DG, NDG). Additionally, gaming experience on gaze behaviour in a racing video game environment was investigated; a one-way ANOVA with group main effect (DG, DNG) was conducted. The analyses for r-NUMFIX and r-DURFIX were run for each AOI. Tukey Honestly Significant Difference tests, Greenhouse-Geisser degrees of freedom adjustments, and Bonferroni multiple-comparison probability adjustments were conducted when necessary. The value alpha was 0.05. Effect sizes were calculated using Partial Eta Squared with 0.02 or

less, approximately 0.13, and 0.26 or more, representing small, medium, and large effect sizes, respectively (COHEN, 1988).

3.3. Results

A complete overview of means and standard deviations of all dependent variables for both driving and gaming experience analyses are provided in Table 3.

Table 3. Means (SDs) of the fixation pattern in each AOI for each group during the simulated racing task.

	Drivers-gamers	Drivers-non-gamers	Pre-drivers-gamers	Group effect (p)
Outside				
r-NUMFIX (unit/min)	1.43 (1.17)	1.75 (2.43)	2.17 (1.29)	*ns*
r-DURFIX (% trial time)	0.59 (0.50)	0.91 (1.78)	0.78 (0.46)	*ns*
Race lane				
r-NUMFIX (unit/min)	137.48 (28.30)	138.09 (14.80)	131.02 (13.02)	*ns*
r-DURFIX (% trial time)	90.30 (13.61)	86.19 (6.59)	78.13 (9.60)	0.042
Chronometer				
r-NUMFIX(unit/min)	3.07 (3.34)	1.91 (3.23)	5.31 (3.99)	*ns*
r-DURFIX (% trial time)	1.57 (2.06)	1.20 (2.43)	3.10 (2.50)	*ns*
Speedometer				
r-NUMFIX (unit/min)	4.27 (4.17)	0.80 (1.12)	3.49 (4.33)	*ns*
r-DURFIX (% trial time)	1.95 (2.36)	0.37 (0.54)	1.64 (2.25)	*ns*

r-NUMFIX: relative number of fixations; r-DURFIX: relative fixations duration; *ns*: nonsignificant ($p > 0.05$).

Driving experience: drivers-gamers vs. non-drivers-gamers

For the r-NUMFIX, the analysis revealed no effect of group on all AOIs: outside, $F(1,18) = 1.757$, $p = .202$, $\eta p2 = .089$; race lane, $F(1.18) = .430$, $p = .520$, $\eta p2 = .023$; chronometer, $F(1,18) = 1.844$, $p = .191$, $\eta p2 = .093$; and speedometer, $F(1,18) = .168$, $p = .687$, $\eta p2 = .009$. For the r-DURFIX, the ANOVA one-way revealed a main effect of group on the AOI race lane, $F(1,18) = 5.336$, $p = .033$, $\eta p2 = .229$. The DG spent more time performing fixations towards the race lane than NDG (Figure 9). There was no group main effect for the r-DURFIX on other AOIs: outside, $F(1,18) = .739$, $p = .401$, $\eta p2 = .039$; chronometer, $F(1,18) = 2.215$, $p = .154$, $\eta p2 = .110$; and speedometer, $F(1,18) = .093$, $p = .764$, $\eta p2 = .005$. For the horizontal and vertical variance of fixations, the analyses revealed no main effect of group, $F(1,18) = .040$, $p = .843$, $\eta p2 = .002$ and $F(1,18) = 1.676$, $p = .212$, $\eta p2 = .085$, respectively.

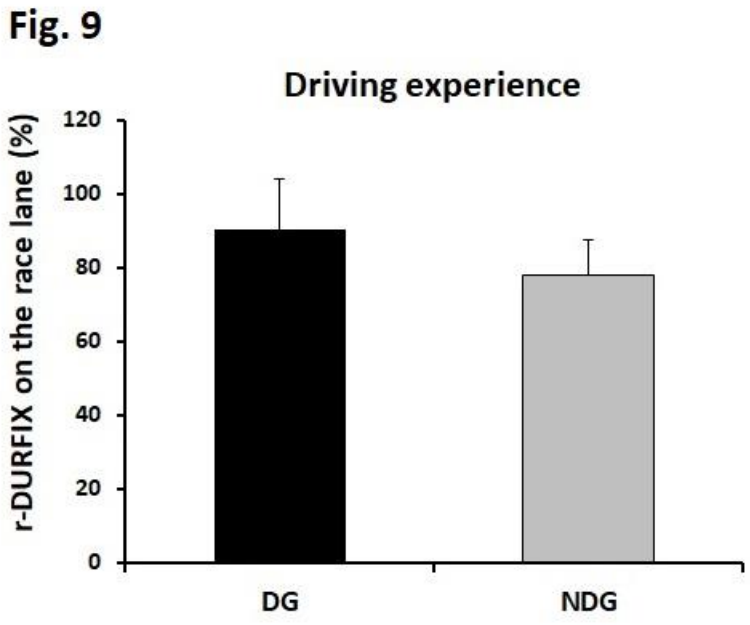


Figure 9: Relative fixations duration (%) on the AOI race lane for the driving experience comparison (drivers-gamers vs. non-drivers-gamers).

Gaming experience: drivers-gamers vs. drivers-non-gamers

For the r-NUMFIX, the analysis revealed a main effect of group on the AOI speedometer, $F(1,18) = 6.424$, $p = .021$, $\eta p2 = .263$. The DG showed a greater number of fixations towards speedometer than DNG during the racing task. There was no group main effect for the r-NUMFIX on other AOIs: outside, $F(1,18) = .135$, $p = .717$, $\eta p2 = .007$; race lane, $F(1,18) = .004$, $p = .952$, $\eta p2 = .000$; and chronometer, $F(1,18) = .621$, $p = .441$, $\eta p2 = .033$. For the r-DURFIX, the analyses revealed no effect of group on all AOIs: outside, $F(1,18) = .296$, $p = .593$, $\eta p2 = .016$; race lane, $F(1.18) = .739$, $p = .401$, $\eta p2 = .039$; chronometer, $F(1,18) = .137$, $p = .716$, $\eta p2 = .008$; and speedometer, $F(1,18) = 4.230$, $p = .055$, $\eta p2 = .190$. For the horizontal and vertical variance of fixations, the analyses revealed no effect of group, $F(1,18) = .011$, $p = .918$, $\eta p2 = .001$ and $F(1,18) = 2.543$, $p = .128$, $\eta p2 = .124$, respectively. Regarding to the performance, the analysis revealed a group main effect for the total race time, $F(1,18) = 6.892$, $p = .017$, $\eta p2 = .277$. The DG performed the racing task faster than the DNG, showing a reduced total race time. The statistically significant differences found for both r-NUMFIX on the speedometer and the total race time between the groups (Figure 10) indicate that gaming experience increased the number of fixations towards speedometer and reduced the total race time of drivers in a racing video game environment.

Fig. 10

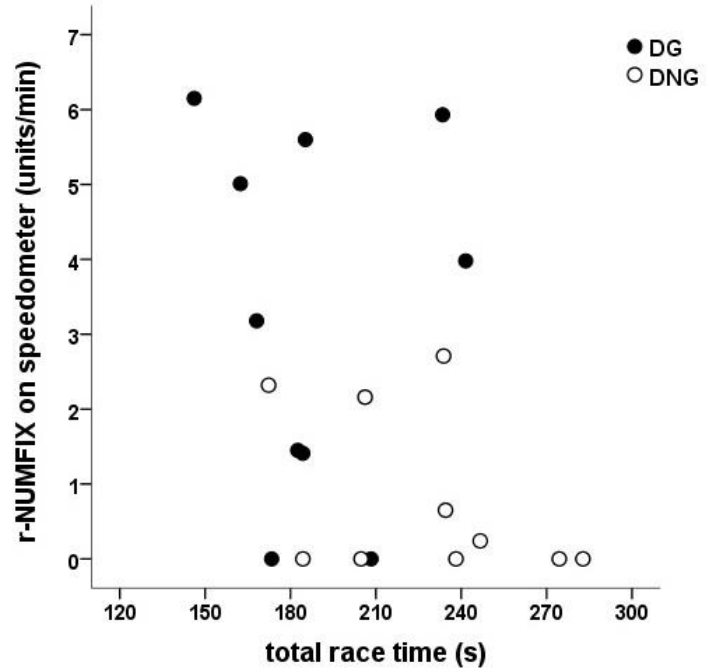


Figure 10: Relative number of fixations (axis y) by total race time (axis x) for the gaming experience comparison (drivers-gamers vs. drivers-non-gamers).

3.4. Discussion

The aim of this study was to investigate the effects of combining experiences of natural driving and race gaming on gaze behaviour and performance of drivers during a simulated racing task. Differences between drivers-gamers and drivers-non-gamers were expected to represent effects of the experience in playing racing video games while differences between drivers-gamers and non-drivers-gamers were expected to represent effects of the experience due to natural driving practice. It was hypothesized that the most experienced participants, the drivers-gamers, would exhibit a task-specific gaze location strategy that combines the smallest relative number of fixations and the largest relative fixation durations, mainly directed to relevant areas of the visual scene, with the shorter total race time (i.e., faster performance). The results revealed that the drivers-gamers spent more time performing fixations towards the race lane than non-drivers-gamers; the drivers-gamers also showed a greater relative number of fixations in the speedometer and performed faster the racing task as compared to the drivers-non-gamers. In the current study, the approach was focusing on the combined driving-gaming experience; the contribution of each factor, driving and gaming experiences, was separately considered.

Driving experience

Combining experiences of natural driving and race gaming affected gaze location strategy of drivers in video game context. Drivers-gamers showed larger relative fixations durations on the race lane (i.e., a relevant area of the visual scene) compared to non-drivers-

gamers. This result partially confirms this study main hypothesis about the effects of natural driving practice on gaze behaviour of gamers. In car driving, visual cues from lane provide essential information to the steering control (LAND; HORWOOD, 1995; LAND; LEE, 1994). In addition, previous study evidenced that, in a simulated driving task, non-drivers-gamers ignored traffic road signs and relevant areas of interest compared to drivers-gamers (CICERI; RUSCIO, 2014). It has been shown that playing racing video games enhance oculomotor performance and visual abilities of regular gamers compared to non-gamers (CASTEL et al., 2005; DYE et al., 2009). However, when comparing experienced gamers with and without natural driving practice in a racing video game task, the gaze location strategy was adapted by the experience due to licensing process. Regarding to the performance, the results revealed non-significant difference between drivers-gamers and non-drivers-gamers during the racing task. One possible explanation for the similarity between drivers-gamers and non-drivers-gamers on performance outcome is related to the familiarization of both groups with the video game environment. In both groups, the experienced gamers reported a regular race gaming practice at the minimum frequency of three times per week with one hour per session. Therefore, the driving experience in natural context does not seem to account for improvement of performance of gamers in a racing video game task.

Gaming experience

Combining experiences of natural driving and race gaming affected gaze location strategy of drivers in video game context. Drivers-gamers more often inspections on the speedometer were accompanied by faster performance during the racing task compared to the drivers-non-gamers. This result confirms this study main hypothesis about the effects of race gaming experience on gaze strategy and performance of drivers. The superior performance among drivers-gamers was associated with increased monitoring of the speedometer. It seems that the attention of the drivers-gamers was shifted toward task-relevant information, arguably in an attempt to consciously adhere to speed instructions. This result corroborates previous findings according to which playing video games provides an improvement in visual attention and oculomotor performance of users (CASTEL et al., 2005; DYE et al., 2009). Although both groups had similar experience in natural driving context, drivers-non-gamers were unable to seek for useful information in relevant areas of the visual scene in a racing video game task. It seems important to consider that the experimental task of this study was performed in a video game environment. In this case, the drivers-gamers were more familiar with the racing lane than the drivers-non-gamers and, therefore, they were more committed to the task instructions and drove as fast as possible. The level of realism of the racing game is also an aspect to be considered for the understanding of the drivers-non-gamers behaviour. In the current study, the racing video game was configured by means that the aspects of the game scenario could represent, or at least be as close as possible, the real-world driving environment. For instance, the players' viewpoint was positioned inside the vehicle rather than the third person, the presence of driving accessories such as steering wheel, brake and accelerator pedals, as well as the speedometer, and the use of high-quality visual characteristics such as texture, luminosity and colours provided to the game content a highly realistic environment to the drivers. It is still controversial if the virtual environment can present a high level of fidelity compared to the natural world environment. VAN LEEUWEN and colleagues (2015) investigated the effects

of visual fidelity on driving performance and gaze behaviour in a driving simulator study. The high-fidelity level scenario (e.g., textured environment) resulted in higher mean driving speeds and increased horizontal gaze variance than the lower fidelity levels (VAN LEEUWEN et al., 2015). On the other hand, it has been argued that lower visual fidelity driving simulator can be competent in driver training, in addition to having economic advantages compared to highly realistic simulation (DAHLSTROM et al., 2009). In the current study, the essential characteristics of visual information provided by the virtual environment appeared to be quite similar to those available in a natural driving context (e.g., optic flow and perception of depth); since that all drivers-non-gamers were able to follow to the task instructions and they performed the task. It seems that the slower performance in the racing task by the drivers-non-gamers is due to the lack of racing video game practice rather than the low visual fidelity of the virtual scenario. Further investigations are needed to examine the behaviour of racing gamers in driving simulators with complex road interactions and a highly realistic urban environment.

The combination of experiences in natural driving and race gaming provided the allocation of the gaze towards areas of interest in the visual scene in order to obtain task-relevant information. The driving training in a virtual environment (e.g., race gaming and/or car driving simulators) might be aligned with the experience in natural driving context. Further investigations are needed to understand the relationship between driving experience in real-life and in racing video games and its effects of perceptual and motor behaviour. Particularly, the use of racing video games as an alternative training in the licensing learning and the natural driving practice for novice drivers, anxious drivers, elderly with or without a neurodegenerative disease (e.g., Parkinson's disease, Alzheimer) who still maintain the driving license.

Limitations of the research

Although a full factorial design and availability of baseline for all factors (e.g., a group of non-drivers-non-gamers) may be desirable, the comparison between drivers-non-gamers and non-drivers-gamers groups was not intended. Here the approach was focusing on the combined driving-gaming experience (drivers-gamers group), testing for removal of each individual experience factor: gaming experience (drivers-non-gamers group) and driving experience (non-drivers-gamers group). In addition, there was a lack of subjective measure data on participants' level of immersion in the game and/or how realistic did the users judge the gaming scenario. This information could illustrate the debate on visual perception while driving and effects of gaming/driving experience. We plan for future studies focusing on pupillometry analyses as a way of discussing mental workload and a variety of potential effects of interest, such as attentional task requirement and immersion in the game.

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Chapter 4.

Parkinson’s disease affects gaze behaviour and performance of drivers

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Abstract

The aim of this study was to investigate the effects of PD and aging on gaze behaviour and performance of drivers in a simulated task. Ten drivers with PD, ten neurologically healthy older drivers, and ten neurologically healthy younger adult drivers were asked to drive in a car simulator for three minutes, maintaining car speed between 100 and 120 km/h and avoiding collisions. Driver's eye movements were recorded. Drivers with PD had more collisions and spent less time driving within the speed zone than the younger-drivers. Drivers with PD performed an increased number of fixations towards task-irrelevant areas of the visual scene and higher visual entropy, indicating a more random gaze behaviour. Older drivers restricted their visual search to the lane area in order to detect threat-related stimuli. PD led to drops in performance of drivers in the car simulator.

Keywords: Parkinson's disease; aging; visual entropy; eye movements, driving simulator.

4.1. Introduction

According to the World Health Organization about 1.25 million people die by traffic accident and about 20 to 50 million victims become disabled by non-fatal crashes each year worldwide (WORLD HEALTH ORGANIZATION, 2016). Among the leading causes of death in Brazil, traffic crashes kill more than 40 thousand people per year (INSTITUTO DE PESQUISA ECONÔMICA APLICADA, 2015; WORLD HEALTH ORGANIZATION, 2015). As populations around the world are rapidly aging, the number of older drivers and/or with disorders associated with the aging process, such as Parkinson's disease (PD) and Alzheimer's disease is likely to increase. Although driving impairments occur in PD patients, the higher involvement in motor vehicle accidents compared to their age-matched pairs is still not well established (RANCHET; DEVOS; UC, 2020; THOMPSON et al., 2018; UENO et al., 2018; ZESIEWICZ et al., 2002).

PD is characterized by motor symptoms, and additional symptoms including losses in cognitive functions (e.g., loss of processing multiple resources in dual-tasks) and impairments in visual skills (e.g., lower contrast sensitivity, deficits in the visual processing, more erratic eye movements during visual target detection in the peripheral area under different eccentricities and reduced useful field of view - UFOV), which can affect driving performance (CRIZZLE et al., 2012; UC, E. et al., 2006; UC, E. Y. et al., 2007). Particularly, drivers with PD showed less visual search accuracy in identifying targets while driving in a simulator compared to their pairs (RANCHET et al., 2020) and a reduced saccades amplitude during visual scanning tasks due to the Basal Ganglia dysfunction (MATSUMOTO et al., 2012). Regarding driving performance, PD patients have showed significantly worse driving performance (i.e., driving in a slower velocity, more often lane deviation and unsafe driving behaviour such as stopping in inappropriate circumstances) compared to neurologically healthy individuals (UC, E. et al., 2006; UC, E. Y. et al., 2007). Decreased safety in PD drivers can also occur due to cognitive and perceptual skills deterioration due to the disease progresses. During a driving simulation task under low-contrast visibility conditions, drivers with PD presented poorer vehicle control and a higher risk for accidents (UC, E. et al., 2009). In addition, PD-drivers identified significantly less landmarks and traffic signs, and they committed more driving errors than their age-matched drivers (UC, E. et al., 2006). Overall, driving is intrinsically linked to visual perception and the investigation of the adverse effects of PD on visual and motor skills is essential. In other locomotion tasks, such as walking around an obstacle and/or walking to step onto targets on the floor, people with PD have shown a greater engagement to the visual information than their age-matched pairs (SIMIELI et al., 2017; VITÓRIO et al., 2016). While walking along a pathway and aiming to step onto targets, PD patients showed more often stepping errors (i.e., erroneous foot placement onto targets) and directed their gaze earlier towards the first target than the control group (VITÓRIO et al., 2016). Additionally, people with PD made more stepping adjustments during the approach walking and at the moment of obstacle circumvention – with longer gaze fixations on the pathway and obstacle than in other areas of the visual scene – compared to the control group without PD (SIMIELI et al., 2017). In both studies, the authors suggested that PD patients were more dependent on visual information to make on-line corrections and stepping adjustments, which seems to be due to deficits on working memory and/or executive functions provoked by the disease (SIMIELI et al., 2017; VITÓRIO et al., 2016). In driving, these cognitive deficits

might be reflected in longer gaze fixations to acquire the relevant visual information for controlling the vehicle compared to drivers without PD.

Furthermore, age-related changes on perceptual and motor behaviour could contribute per se to decreased driving performance. Older drivers – neurologically healthy individuals – have shown a reduced UFOV, which is associated with a higher likelihood to incur in crash accidents (OWSLEY et al., 1998), slower reaction time in dual-task driving (LEVERSEN et al., 2013), and more erratic saccadic eye movements during visual target detection in peripheral area under different eccentricities (BEURSKENS; BOCK, 2012) compared to young adult drivers. Elderly drivers can be characterized as suffering from a loss of multiple resources processing in more complex tasks and, consequently, this limitation may reflect on gaze behaviour (SCHIEBER; GILLAND, 2008). In a dual-task driving experiment, as cognitive demand increased, older drivers showed lower visual entropy compared to the low-demand dual-task and the single-task conditions; while younger drivers showed non-significant changes on eye movements' pattern with manipulation (SCHIEBER; GILLAND, 2008). The visual entropy has been used as a new metric in the assessment of the gaze behaviour (GOTARDI et al., 2018; HOLMQVIST et al., 2011; SHIC et al., 2008). Based on Information Theory (SHANNON, 1948), where entropy is related to system complexity, lower entropy values correspond to a more ordered pattern of eye movements while higher visual entropy would indicate a more random visual scanning (SCHIEBER; GILLAND, 2008). It has been argued that high values of entropy may indicate an inclination for exploration while lower visual entropy would refer to a more restricted visual exploration (SHIC et al., 2008). These changes in gaze behaviour over the years can affect elderly drivers in controlling the vehicle and detecting task-relevant information. Thus, it is expected that the aging process would have an adverse impact on gaze behaviour (BEURSKENS; BOCK, 2012; OWSLEY et al., 1998; SCHIEBER; GILLAND, 2008) as well as a decline in driving performance (LEVERSEN et al., 2013; OWSLEY et al., 1998), regardless of the presence of neurodegenerative diseases such as PD. Therefore, the distinction between the effects of Parkinson's disease and those from aging on gaze behaviour and motor performance of drivers becomes necessary.

The aim of the study was to identify the effects of PD and aging on gaze behaviour and performance of drivers in a simulated task. It was expected that drivers with PD would exhibit a poorer performance in the driving simulator, showing a greater difficulty in control the speed vehicle and also a higher crashes involvement (CRIZZLE et al., 2012), compared to the older and younger drivers; whereas older people would drive more in erroneous speed compared to young adults, corroborating previous findings (LEVERSEN et al., 2013; OWSLEY et al., 1998). In terms of gaze behaviour, it was supposed that drivers with PD would show a greater number of gaze fixations and longer fixation time compared to older and younger drivers. As UC and colleagues (UC et al., 2006) found that drivers with PD identify less task-relevant information than neurologically healthy drives; it was expected that PD-drivers would perform fewer fixations towards relevant areas of the visual scene (i.e., lane, rearview mirror, and speedometer) than older and younger drivers. In addition, it was hypothesized that older drivers neurologically healthy would exhibit lower visual entropy compared to the younger drivers, corroborating previous study (SCHIEBER; GILLAND, 2008), due to their more restricted multiple resources processing provoked by aging process. Regarding the PD-drivers group, it was also expected a more ordered pattern of eye movements (i.e., low values of visual entropy)

than young adults, as a result of the visual/cognitive deficits provoked by the disease, indicating a dysfunctional more restricted visual scanning behaviour.

4.2. Method

Participants

Thirty active and licensed drivers voluntarily participated in this study. Ten drivers with PD (PD-drivers), ten neurologically healthy older adult drivers (older-drivers), and ten neurologically healthy younger adult drivers (younger-drivers) participated in a driving simulator task (Table 4). To avoid the effects of driving experience, only experienced drivers who reported more than 30,000 kilometres driven were selected in all groups. See details of drivers' experience quantification in Gotardi and colleagues (GOTARDI et al., 2019). To control the participants' visual acuity, the Snellen test was conducted and individuals who obtained scores between 20/20 and 20/30 were selected. Participants signed out the informed consent prior to any intervention approved by Ethical Local Committee (#45169015.2.0000.5505).

Table 4. Means (SDs) for characteristics of the participants (n=30). Disease duration, Hoehn and Yahr stage, UPDRS are non-applicable (N/A) for both young and older adults.

	Younger drivers	Older drivers	PD drivers
Age (years)	26.5 (3.1)	69.8 (3.4)	66.0 (6.0)
Weight (kg)	82.7 (17.1)	91.0 (8.4)	67.4 (16.3)
Height (m)	177.8 (6.3)	163.1 (6.8)	164.6 (5.9)
Disease duration (years)	N/A	N/A	6.7 (3.0)
Hoehn and Yahr stage*	N/A	N/A	2.2 (0.4)
UPDRS-III (pts)*	N/A	N/A	19.3 (6.1)
MMSE (pts)*	N/A	28.5 (1.1)	28.2 (1.8)

Note: UPDRS – Unified Parkinson's Disease Rating Scale; MMSE – Mini-Mental State Examination; * in ON-state of medication.

Driving simulator

The training car simulator City Car Driving (Forward Development, Home Edition, version 1.5) was configured to simulate a Brazilian driving scenario. The software was run on a Dell computer (Windows 10) in which was attached to a cockpit (XT Premium V2 Racing Extreme) with a Gamer Logitech G27 driving controllers (steering wheel, turning signals, brake, accelerator and clutch pedals, a gearbox of five speeds and the reverse) and a TV screen (Samsung 46") placed at 100 cm away from participants' seat. The driving simulator was configured in Free driving mode: i) area: multi-lane highway; ii) transport: left-handed car with manual gearbox, power 1.2; iii) traffic: 20% of vehicle traffic density, 0% of passenger traffic density, emergency situations to not occur; iv) weather/visibility: summer, clear, daytime. Participants' perspective was configured as the driver-view from inside the vehicle, including

the rear-view mirrors (left, right, and central) and a digital speedometer (figure 11a). Accelerator and brake pedals were set up in 50% of pressing speed and steering wheel sensitivity was reduced to zero in order to approximate to the real-life experience. Potential distractors such as show violation messages, controls indication and/or GPS instructions were disabled. The route consisted in driving straight ahead in a multi-lane highway. No unexpected route deviation was programmed in the software. If any participant deviated from the original route, the task was interrupted and, after clarification of the task instructions, it was resumed. Participants were free to adopt overtaking strategy in order to avoid collisions and/or to maintain the vehicle speed. Traffic behaviour was typical to metropolitan highways with vehicles in the left lanes driving in higher speed than those in the right ones. Dangerous traffic events were not configured. Collisions would occur by unsuccessful overtaking manoeuvre (including not using the turning signals) and/or driving too fast or too slow in the wrong lane. When collisions occurred, test timer was stopped, and the experimenter set the simulator to start at the same location where the collision occurred. Once the participant was ready to perform again, timer was released. In total, participants drove 3 min of consecutively driving.

Eye-tracking

Eye movements were recorded using a Head-Mounted Eye Tracker (model H6, Applied Science Laboratory), at a sampling rate of 60 Hz. This video-based analysis system of eye movements contains two micro-cameras, one that films the eye and another one the scene, attached to a headgear that was anatomically adjusted to the participant's head. In the eye video, pupil and corneal reflection centroids were identified and the vector between both is used to determine horizontal and vertical coordinates of eye position in the scene video (figure 11b).

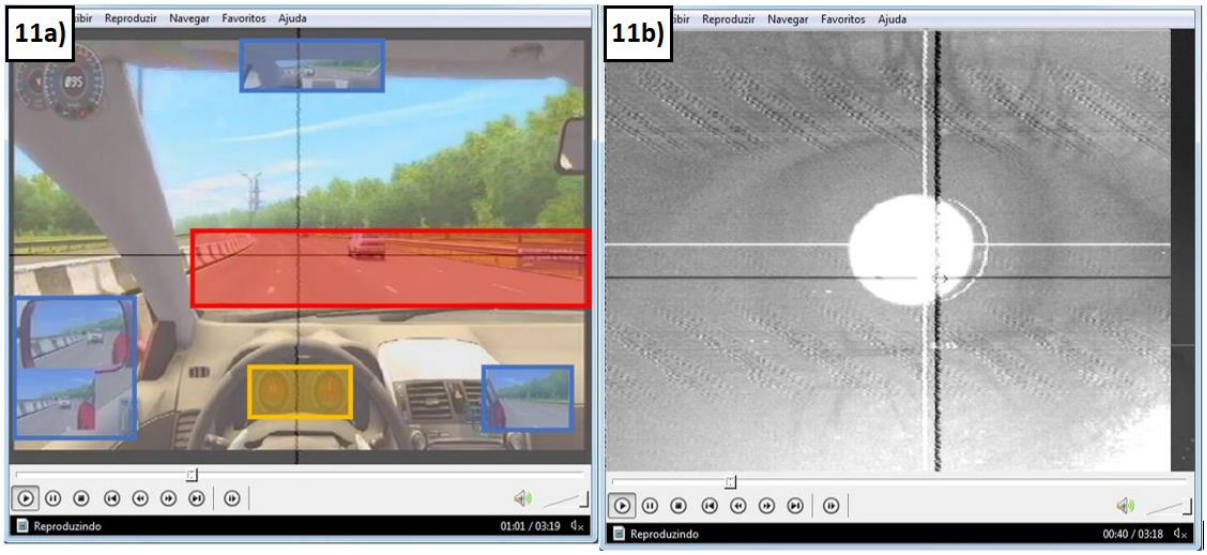


Figure 11: a) screenshot from Eye Tracker scene video (participants' view in the simulator) with the black cursor representing the eye position. AOIs: lane (red), speedometer (yellow), and rear-view mirrors (blue); b) screenshot from Eye Tracker eye video with the pupil cursor (black) and the corneal reflection cursor (white).

Procedure

Drivers with PD were tested during their ON-state of medication of the PD (i.e., approximately one hour after taking the dose of LEVODOPA). Prior to the start of the test, participants were asked to take a seat in the cockpit and had the eye tracker's headgear adjusted on their head. A nine-point calibration was conducted to adjust the eye tracker accuracy. Participants were asked to drive during three minutes on the highway and maintaining car speed between 100 and 120 km/h and avoiding collisions. Participants had three minutes to familiarize themselves with the simulator and equipment before the experimental starting. Trial start was timed when drivers reached 100 km/h for the first time.

Data analysis

In offline frame-by-frame video analysis, driving performance was assessed by both the percentage of time driving within the speed range (%VEL) and the number of collisions (COL) made throughout the trial. The %VEL was considered by the period of time (s) that car's speed remained within the speed range (i.e., 100 – 120 km/h) divided by the total trial's time and multiplied by 100. The number of collisions per trial was counted during the time valid within the trial determining the COL for each participant. The coefficients of variation of %VEL (%VEL-cv) and COL (COL-cv) were computed to provide the variability of the car speed and the number of collisions throughout trial, respectively. It was calculated using the standard deviation of the data divided by the average of the data and multiplied by 100, in order to normalize the variation of the signal in relation of its magnitude.

The ASL Results Plus software (version 1.8.2.18, ASL) was used for eye movements analysis. In order to assess how often visual inspections were made and for how long these inspections last, both the total number of fixations (nFIX) and total fixations duration (dFIX) were calculated for each participant. Fixation detection criteria included a minimum duration of 100 milliseconds and the spatial limit of 1 degree of visual angle. The coefficients of variation of nFIX (nFIX-cv) and dFIX (dFIX-cv) were computed to calculate the variability of the nFIX and dFIX, respectively. Additionally, analyses by Areas of Interest (AOIs), two-dimensional (2-D) regions defined on the viewing plane were made (figure 11a). Four AOIs were considered: i) lane, which provides the essential visual information to steering control; ii) speedometer, task-relevant information; iii) rearview mirrors, task-relevant information for deciding overtakes; and iv) outside, any part of the visual scene not considered an AOI. The total number of fixations and total fixations duration were calculated per AOI.

Entropy was applied to identify whether drivers' visual scanning behaves randomly or, alternatively, more predictably as a result of PD and/or aging. The entropy was quantified based on Information Theory (Shannon, 1948) through to the conditional transition-probability matrices between AOIs. When entropy is high, drivers fixated their gaze on all AOIs an equal number of times and will make gaze transitions between all possible combinations of AOIs with a near equal frequency. Alternatively, lower entropy indicates that gaze fixations pattern become more ordered, less complex. The entropy was calculated following the Equation 4:

$$H(R) = -\sum_{r_i} p\,(r_i) log_2\, p(r_i), r_i > 0 \qquad (4)$$

where R is a normalized transition matrix and r_i are cell values of that matrix with probabilities $p(r_i)$.

Finally, the relative entropy was measured by dividing the observed entropy by the maximum value of entropy. The relative entropy allows the comparison of results across groups and other studies (Schieber & Gilland, 2008).

Statistical analysis

The one-way ANOVAs with a between-subject group factor (younger-drivers, older-drivers, PD-drivers) were performed on the following dependent variables: i) Driving performance – %VEL, %VEL-cv, COL, COL-cv; ii) Overall fixations pattern – nFIX, nFIX-cv, dFIX, dFIX-cv and relative entropy; and iii) visual scanning across AOIs – nFIX-aoi and dFIX-aoi. Statistical analyses were run using SPSS Statistics (17.0.1). Tukey Honestly Significant Difference tests, Greenhouse-Geisser degrees of freedom adjustments, and Bonferroni multiple-comparison probability adjustments (Threshold = .0166) were conducted in statistical analyses as necessary. The value alpha was .05. Effect sizes were calculated using Eta Squared with 0.02 or less, approximately 0.13, and 0.26 or more, representing small, medium, and large effect sizes, respectively (Cohen, 1988).

4.3. Results

Driving performance

For the %VEL and COL (Figure 12), the analysis revealed a main effect for group, $F(2,27) = 49.716$, $p < .001$, $\eta p2 = .786$ and $F(2,27) = 7.353$, $p = .003$, $\eta p2 = .353$, respectively. Post-hoc tests indicated that both groups of elderly drivers, with or without PD, spent less time driving within the required speed range (100-120 km/h) throughout total trial time, PD-drivers: 6.76 ± 9.56 % of total trial time and older-drivers: 13.72 ± 20.52 % of total trial time compared to younger-drivers: 71.01 ± 13.45 % of total trial time. Particularly, PD-drivers spent 35.28 ± 22.53 % of total trial time driving within 01-60 km/h, 52.68 ± 22.19 % of total trial time driving within 61-99 km/h, and 0.09 ± 0.22 % of total trial time driving above 121 km/h. Older-drivers spent 27.57 ± 16.17 % of total trial time driving within 01-60 km/h, 52.55 ± 23.98 % of total trial time driving within 61-99 km/h and 0.34 ± 0.89 % of total trial time driving above 121 km/h. Finally, younger-drivers spent 0.10 ± 0.001 % of total trial time driving within 01-60 km/h, 1.52 ± 2.59 % of total trial time driving within 61-99 km/h, and 8.97 ± 0.10 % of total trial time driving faster than 121 km/h. Older- and PD-drivers spent most part of the total trial time driving slower than the required speed range. Furthermore, PD-drivers performed higher rate of collisions than younger-drivers. Yet, there were no differences between younger-drivers and older-drivers or older-drivers and PD-drivers. For both %VEL-cv and COL-cv there was no significant main effect for group, $F(2,27) = 3.060$, $p = .063$, $\eta p2 = .185$ and $F(2,27) = 1.592$, $p = .222$, $\eta p2 = .105$, respectively.

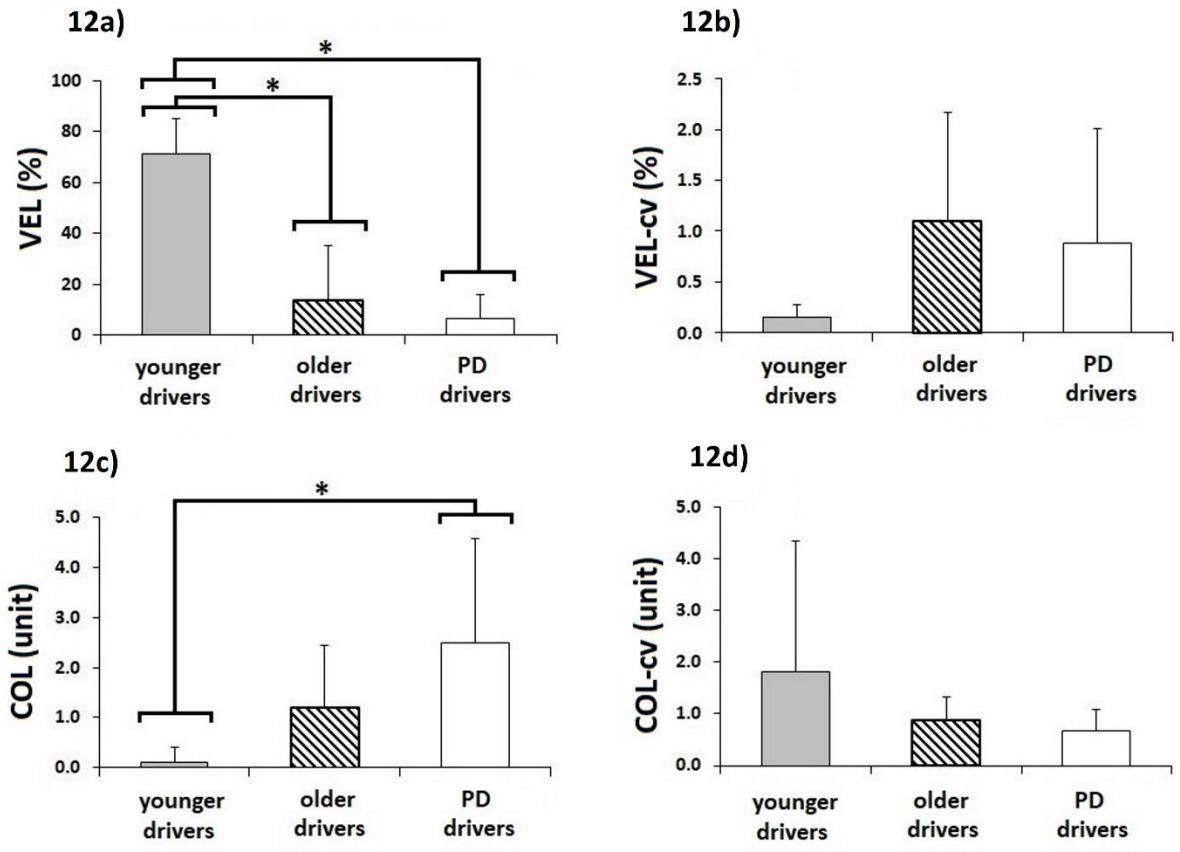


Figure 12: a) Percentage of total trial time that participants spent driving within the speed range (%VEL); b) Coefficient of variation of the %VEL (%VEL-cv); c) Number of collisions (COL); and d) Coefficient of variation of the COL (COL-cv) per group.

Overall fixations pattern

For the nFIX and nFIX-cv (Figure 13), the analyses revealed a main effect for group, $F(2,27) = 3.705$, $p = .038$, $\eta p2 = .215$ and $F(2,27) = 4.934$, $p = .022$, $\eta p2 = .246$, respectively. Post-hoc tests indicated that PD-drivers performed a greater nFIX than older-drivers, but showed no differences compared with younger-drivers or between older-drivers and younger-drivers. Furthermore, PD-drivers showed greater nFIX-cv compared to younger-drivers, but no differences in comparison to older-drivers. For the dFIX and dFIX-cv (figures 2C and 2D) the analyses revealed a main effect for group, $F(2,27) = 4.451$, $p = .021$, $\eta p2 = .248$ and $F(2,27) = 5.606$, $p = .009$, $\eta p2 = .293$, respectively. PD-drivers performed shorter dFIX than younger-drivers, but no differences between PD-drivers and older-drivers. Furthermore, PD-drivers showed higher dFIX-cv compared to older and younger-drivers.

For the relative visual entropy (Figure 14), the analysis revealed a main effect for group, $F(2,27) = 5.300$, $p = .011$, $\eta p2 = .282$. PD-drivers showed higher visual entropy compared to younger-drivers, but no differences to older-drivers neither between younger nor older-drivers.

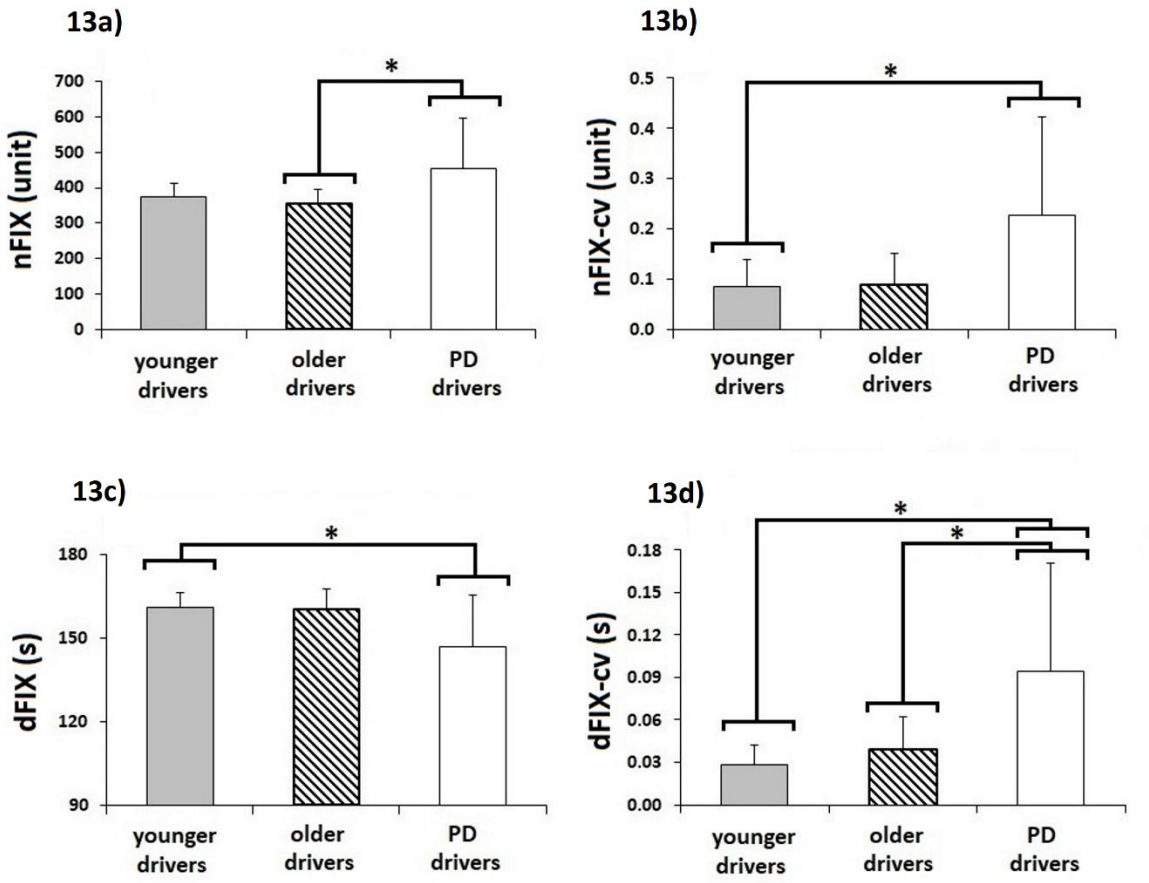


Figure 13: a) Total number of fixations (nFIX); b) Coefficient of variation of the total number of fixations (nFIX-cv); c) total fixations duration (dFIX); and d) Coefficient of variation of the total fixations duration (nFIX-cv).

Fig. 14

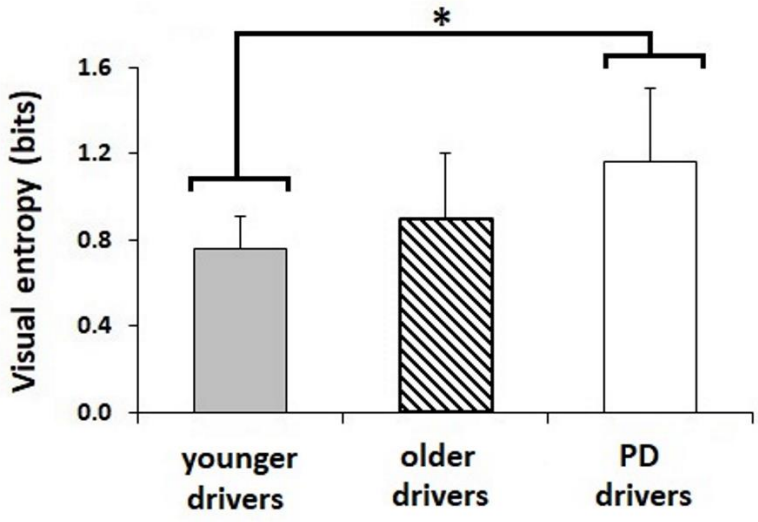


Figure 14: Visual entropy (bits) per group.

Visual scanning across AOIs

A complete overview of means and SDs of the gaze behaviour in each AOI is provided in Table 5. For the n-FIX on the AOI outside, the analysis revealed a main effect for group, $F(2,27) = 4.018$, $p = .030$, $\eta p2 = .229$. PD-drivers performed a greater n-FIX towards outside (irrelevant stimulus) than younger-drivers, but there were no differences in comparison to older-drivers. For the d-FIX on the outside, there was non-significant effect for group, $F(2,27) = 2.086$, $p = .144$, $\eta p2 = .134$. For the d-FIX on the lane, the analysis revealed a main effect for group, $F(2,27) = 4.063$, $p = .029$, $\eta p2 = .231$. Post-hoc tests indicated that PD-drivers spent less time fixating at the lane compared to older-drivers, while showed no differences to younger-drivers. For n-FIX towards lane, the analysis revealed no main effect for group, $F(2,27) = 3.327$, $p = .051$, $\eta p2 = .198$. For the n-FIX and d-FIX on the speedometer, the analyses revealed a main effect for group, $F(2,27) = 7.277$, $p = .003$, $\eta p2 = .350$ and $F(2,27) = 5.867$, $p = .008$, $\eta p2 = .303$, respectively. Younger-drivers spent more time looking, performing a greater n-FIX, towards the speedometer than older-drivers. There were no significant differences between PD-drivers to younger-drivers and older-drivers. For the n-FIX and d-FIX on the AOI rearview mirrors, the analyses revealed no main effect for group, $F(2,27) = 1.063$, $p = .359$, $\eta p2 = .073$ and $F(2,27) = .295$, $p = .747$, $\eta p2 = .021$, respectively.

Table 5. Means (SDs) for the gaze behaviour of each group across AOIs (n=30).

	Young drivers	Older drivers	PD drivers
Outside			
nFIX (units)	1.60 (2.17)	3.10 (3.28)	8.40 (8.93)
dFIX (s)	0.53 (0.81)	0.79 (1.23)	1.85 (2.19)
Lane			
nFIX (units)	274.10 (42.60)	307.70 (46.64)	388.30 (164.53)
dFIX (s)	130.38 (15.86)	149.33 (13.02)	126.25 (26.39)
Speedometer			
nFIX (units)	61.10 (24.71)	16.00 (11.76)	34.10 (37.06)
dFIX (s)	22.16 (12.19)	3.95 (3.20)	12.38 (16.30)
Rearview mirrors			
nFIX (units)	36.80 (18.93)	27.20 (19.24)	24.50 (21.22)
dFIX (s)	7.98 (4.69)	6.04 (4.27)	6.38 (8.32)

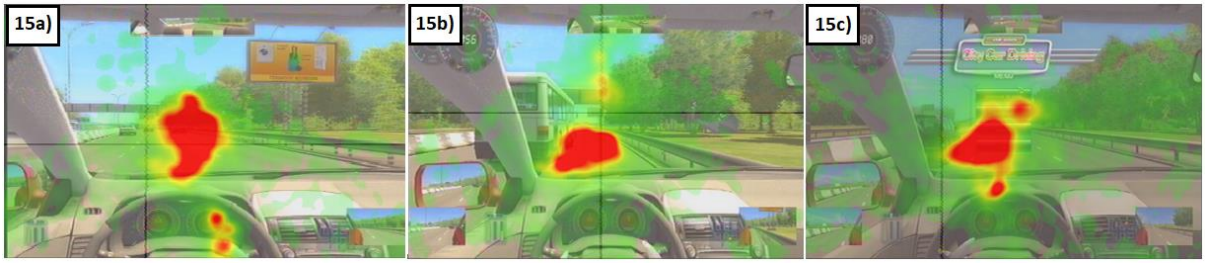


Figure 15: Heat map representing the relative density of visual activity for: a) younger-drivers; b) older-drivers; and c) PD-drivers. Cooler colour (green) represents less visual activity while hot colour (red) indicates the most time spent gazing towards the areas.

4.4. Discussion

The aim of this study was to investigate the effects of PD and aging on gaze behaviour and performance of drivers. The novelty of the manuscript is to contribute with evidence of how PD and aging differently affect the visual scanning pattern in driving. Adverse changes on gaze behaviour may indicate an impaired acquisition of task-relevant information, which can be related to the poorer performance demonstrated by both drivers with PD and elderly drivers. Both PD-drivers and older-drivers distinguished from the performance of the younger-drivers; however, non-significant difference was found between their driving performance, in contrast to previous evidence (ZESIEWICZ et al., 2002). The results of the present study revealed that PD-drivers were more involved in simulated car collisions and spent less time driving within the speed zone compared to the younger-drivers, confirming that PD disrupts driving performance (CRIZZLE et al., 2012; UC, E. et al., 2006; UC, E. Y. et al., 2007). Moreover, older-drivers also spent more time driving in erroneous speed than younger-drivers, corroborating with previous studies that have showed adverse effects of aging process on driving behaviour (LEVERSEN et al., 2013; OWSLEY et al., 1998). This result partially confirms study main hypothesis about driving performance. One possible explanation for understanding the similarity between PD-drivers and older-drivers is that the simulated driving environment was a challenging task for both groups. The challenging of the task can be increased due to cognitive/motor deficits provoked by both aging process (LEVERSEN et al., 2013; OWSLEY et al., 1998) and PD (CRIZZLE et al., 2012; UC, E. et al., 2006; UC, E. Y. et al., 2007). These deficits affect the drivers' ability to control the vehicle and to detect task-relevant information in the environment, provoking a disrupted perceptual and motor performance. In addition, despite of several studies have used and indicated car driving simulators to scientific research (GOTARDI et al., 2018, 2019; WINTER et al., 2012; ZESIEWICZ et al., 2002), due to the various advantages such as controllability, reproducibility and standardization of the experimental conditions, the time exposure and familiarity of the elderly population (PD and non-PD) to the virtual environment are more restricted compared to young adults (NPD, 2015). In Brazil, 82% of those within the 13-59 age range self-reported as video game players on at least one gaming platform (NPD, 2015). The unfamiliar environment may have demanded much more from both elderly groups (with or without PD) to perform in driving simulator. Although the simulated driving task in this study has lasted a relatively short period of time (i.e., three minutes) in comparison to what drivers usually do in daily real traffic experience; this driving task duration is aligned with previous studies that investigated the behaviour of drivers in virtual environments (GOTARDI et. al., 2018; 2019a; 2019b). All participants, including older- and PD-drivers, were experienced drivers and were able to show a stable driving performance in the simulated environment until the end of the familiarization session. The familiarization session also lasted 3-min of continuous simulated driving, which represents 100% of the total driving task duration. The duration of the familiarization session and the driving task was considered sufficient for investigating perceptual-motor behaviour of drivers. Alternatively, a longer practice time for both groups of elderly drivers compared to the younger one would insert a potential bias of learning on the data.

The analyses of overall pattern of fixations found that PD-drivers performed a greater number of fixations compared to older-drivers and showed a larger variability in both number

of fixations and total fixations duration than both older-drivers and younger-drivers, confirming our hypothesis related to gaze behaviour. Interestingly PD-drivers and older-drivers adopted a different visual search strategy to perform the task. The AOIs analyses indicated that PD-drivers performed a greater number of fixations towards the outside area than younger-drivers, while older-drivers spent more time performing fixations to the lane than PD-drivers. In the present study, three areas of the visual scene were defined as the main sources of task-relevant information to perform the driving task (i.e., lane, speedometer and rearview mirror). The outside area represented any part of the visual scene not considered as an area of interest. Confirming the hypothesis of the study, PD-drivers performed more gaze fixations towards task-irrelevant information (i.e., outside area) compared to younger-drivers, corroborating previous study (UC, E. et al., 2006). Although the PD-drivers of this study increased the overall number of fixations, their visual attention was shifted towards task-irrelevant information which indicates a reduction of the goal-directed control (DERAKSHAN et al., 2009). On the other hand, the superior driving performance among younger-drivers was associated with increased monitoring of the speedometer. It seems that the attention of the younger-drivers was shifted toward task-relevant information, arguably in an attempt to consciously adhere to speed instructions. In contrast, although the older-drivers sought information in a relevant area of the visual scene, they were unable to use the information for maintaining the driving performance. It could be argued that older-drivers restricted their visual search to threat-related stimuli (i.e., other cars on the lane to avoid collisions) rather than keeping the vehicle speed. Since young adults present enough cognitive resources to process both tasks of maintaining the vehicle speed and avoiding collisions, the attentional shifting between the lane and speedometer becomes an efficient visual strategy. However, for older-drivers this dual-task impaired driving performance by the lower capacity of multiple resources processing as a result of the aging process (LEVERSEN et al., 2013; SCHIEBER; GILLAND, 2008).

In contrast to the study's hypothesis, PD-drivers showed higher visual entropy than younger-drivers. Higher entropy corresponds to an unpredictable and more random eye movements' pattern. It still controversial the interpretation of what visual entropy represents on gaze behaviour (GOTARDI et al., 2018; HOLMQVIST et al., 2011; SHIC et al., 2008). It has been argued that a more random visual scanning implies into less acquisition of information as well as a higher effort spent (HOLMQVIST et al., 2011). On the other hand, higher visual entropy may indicate a preference for exploration while low values indicate lower tendency to explore hence fewer areas of interest are visited (SHIC et al., 2008). It can be suggested that PD-drivers sought to explore more the environment in order to detect information and to avoid the performance disruption. However, as AOI analyses evidenced, they were unable to look at the task-relevant areas of the visual scene, indicating an inefficient visual scanning strategy. In studies with locomotion tasks such as walking around an obstacle or walking to step onto visual targets on the floor, people with PD have shown a greater engagement to the visual information than their age-matched pairs (SIMIELI et al., 2017; VITÓRIO et al., 2016). It has been suggested that due to working memory and/or executive functions deficits provoked by the disease, people with PD increase the overall number of fixations to deal with the difficulty remembering of locations and longer period fixating as a result of slower processing capacity (SIMIELI et al., 2017). In addition, the results of the visual entropy in PD-drivers brought new

insights to understand how the disease affects the saccadic eye movements system and, consequently, the motor behaviour.

Both PD and aging led to drops in performance of drivers in the car simulator. Moreover, the underlying attentional mechanisms between older-drivers and PD-drivers showed important differences. PD-drivers performed more gaze fixations, with larger variability, towards task-irrelevant areas of the visual scene and showed higher random gaze behaviour, in attempt to increase the acquisition of information to overcome cognitive deficits provoked by the disease. Meanwhile, older-drivers restricted their visual search to the lane in order to detect threat-related stimuli for avoiding collision rather than keeping the vehicle speed. The current findings suggest that PD-drivers and older-drivers have a limited perceptual and motor driving ability compared to younger-drivers. These findings suggested that PD and aging differently influence drivers' gaze behaviour in a simulated driving task. Considering that driving plays an important social role in the current society, more interventions should be implemented to improve the perceptual and motor abilities of people with PD and elderly people who intend to maintain as an active driver. The car simulators can be a safe environment to develop well-controlled practical strategies for these population, in order to reduce the number of collisions and to achieve safer driving. Eye movements analysis indicated that both the aging process and the PD impair the capture of task-relevant information in driving. Practical interventions aiming to boost visual abilities such as visual search accuracy and/or amplitude of saccades for both older- and PD-drivers should be considered.

Limitations of the research

Subjective data regarding participants' feelings and/or experience in driving a car simulator was not collected. Alternatively, it was informally asked for the participants their experience with driving in a virtual environment and how challenging the simulated task could have been. All participants, including the group of young adults, reported no previous experience with driving in a virtual environment (e.g., car simulators, racing video games) and/or no discomfort and difficulty in performing the task during the test. A familiarization procedure was done prior to the test in order to check whether or not participants would be able to follow the task instructions and show a stable driving behaviour (i.e., total control of the vehicle's speed variation and steering, no difficulties in changing gears, and full domain with the simulator controls). In the present study, the essential characteristics of visual information provided by the virtual environment appeared to be quite similar to those available in natural driving (e.g., optic flow and perception of depth), allowing a realistic task-specific context for the participants. However, due to the short testing duration of 3 min, elderly drivers may not have had sufficient time to establish a stable driving behaviour. The assessment of the perceptual-motor behaviour of older- and PD-drivers in longer protocols will be addressed for further investigations.

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Interlude.

Perception-action coupling

Exploring the role of eye movements in driving inevitably led me to the debate on the role of cognition in the relationship between perception and action. Within cognitive perception frameworks, such as the model-based approach (LOOMIS et al., 1992; LOOMIS; BEALL, 2004), the individual and the environment exist as distinct entities. This division is bridged by the individual's construction of mental representations of the environment. Perception then entails the transformation of cues and stimuli (input) to perceptual representations, which subsequently activate programs that guide action (output). In this paradigm, perception and action are seen as the input and output systems of the cognitive process, with perception preceding and occurring independently of action. Through the examination of drivers' gaze behaviour patterns in Chapters 2, 3, and 4, we observed that the detrimental effects of anxiety, aging, or Parkinson's disease on driving performance were accompanied by a more restricted gaze pattern. Within this context, the observed gaze patterns reflect the allocation of attentional resources to sustain (or minimize the decline in) performance (KONSTANTOPOULOS et al., 2010; LOOMIS et al., 1992; LOOMIS; BEALL, 2004; MARR, 1982; MILLER, 2003; PHILBECK et al., 1997).

Gibson's ecological theory (1979) offers an alternative perspective on the perception-action dynamics. Central to this framework is the affordance-based approach, suggesting that perception directly guides action based on perceived affordances (FAJEN, 2007). This perspective rejects traditional dichotomies such as organism-environment, body-mind, emphasizing instead the immediate and unmediated coupling between perception and action. As GIBSON (1979) argued: “We must perceive to move, but we must also move to perceive” (p. 223). That is, not only optic flow is used to regulate action, but the observer’s movements change the optic flow, generating new affordances available for perception, in a continuous perception-action cycle (FAJEN, 2005b). This unorthodox Gibsonian idea that navigation through the environment is directly guided by optical flow, without the need for cognitive processing, is (to say the least) fascinating. Aligning oneself with the ecological approach entails acknowledging that perception and action must not and cannot be disentangled. Given the contrasting theoretical frameworks, choosing a side seems inevitable. Yet, determining which approach best elucidates the visually guided actions of urban traffic users is not a simple task. Nonetheless, principles such as parsimony and ecological representativity can contribute to this debate.

I.1. Parsimony

The principle of parsimony, also known as Occam’s razor, asserts that when confronted with multiple explanations for the same phenomenon, the simplest one, requiring the fewest assumptions, should be preferred (SOBER, 1981). This principle encourages the formulation of more straightforward hypotheses that are both easier to comprehend and validated through empirical testing. Assessing the principle of parsimony involves considering the simplicity and explanatory power of competing theories (RODRIGUES et al., 2020).

Gibson’s (1979) ecological theory adheres to principle of parsimony by prioritizing perception-action coupling over complex cognitive processes. It centres around three fundamental principles: direct perception, reciprocity between the individual and the environment, and perception-action coupling (FAJEN, 2007; GIBSON, 1979a; WARREN; WHANG, 1987). This approach emphatically ties to minimize reliance on (elaborate) mental

representations, focusing instead on simpler concepts such as optic array and affordances, which are directly perceived as the observer moves through the environment to explain perception and action. Optic array, for example, refers to the ambient array structured by objects, surfaces, and events, thereby directly specifying the properties of the environment. By bypassing the necessity for intermediate cognitive processes, perception becomes a well-posed problem (WARREN, 2021). Regarding explanatory power, the ecological approach thus facilitates our comprehension of visual perception in tasks where optical variables are consistently available and clear. However, it typically overlooks scenarios with absent or conflicting information, such as visual illusion or occlusion tasks. For instance, research has shown that individuals can navigate through environments accurately, even under temporal occlusion conditions, whether walking or driving (GODTHELP, 1985; LOOMIS; BEALL, 2004; PHILBECK et al., 1997). Explaining how the perceptual-motor system manages behaviour without invoking cognitive processes in the absence of optic flow poses a challenge for the proponents of ecological psychology.

Conversely, the cognitive approaches of perception (FODOR; PYLYSHYN, 1981; LOOMIS; BEALL, 2004; MARR, 1982) readily provide explanations for movement regulation under visual occlusion conditions. These theories suggest that the visual system constructs mental representations of the road on the basis of prior knowledge or memory, enabling a continuous perception of the path even when optic flow is absent. However, its explanatory power comes at the cost of increased assumptions (RODRIGUES et al., 2020). These approaches necessitate the involvement of cognitive processes such as attention, memory, and decision-making to elucidate how visual cues or stimuli are transformed into perception. While these cognitive processes remain like riddles in the black box of the brain, they align well with neurophysiological findings that have mapped neural activity related to perception and cognition (MORARESKU et al., 2023; ZHU et al., 2010; ZINK et al., 2016). Nevertheless, by grounding perception and action within the active pickup of information in the ambient array, ecological approaches (FAJEN, 2007; FAJEN; WARREN, 2003; GIBSON, 1979) emerge as more parsimonious than the cognitive frameworks.

Moreover, within the ecological approach, the affordance-based control approach explains perception in terms of possibilities for action. In other words, we perceive what we can do, rather than isolated objects, layouts, shapes and so on to which we have to add meaning to perceive (know) what we can do. This enables us to understand the visual control of actions as based on achieving and sustaining the perception of affordances. In the field of possibilities, different styles of action control are possible. Styles of control refers to invariances over time and place in how movements are organized and executed across individuals and/or conditions (MASELLI et al., 2019). Affordance-based control approach accommodates these variations in movement control, enhancing the explanatory power of the ecological theory of perception (FAJEN, 2005b). Unlike information-based control models, including $\dot{\tau}$ braking strategy (LEE, 1976), which emphasize error-nulling as the sole control style to successful performance, the affordance-based approach recognizes error-nulling as just one among several control styles. That is, different styles of control would result in successful action as long as the required action remains within the maximum action capabilities boundary (see Figure 16).

Fig. 16

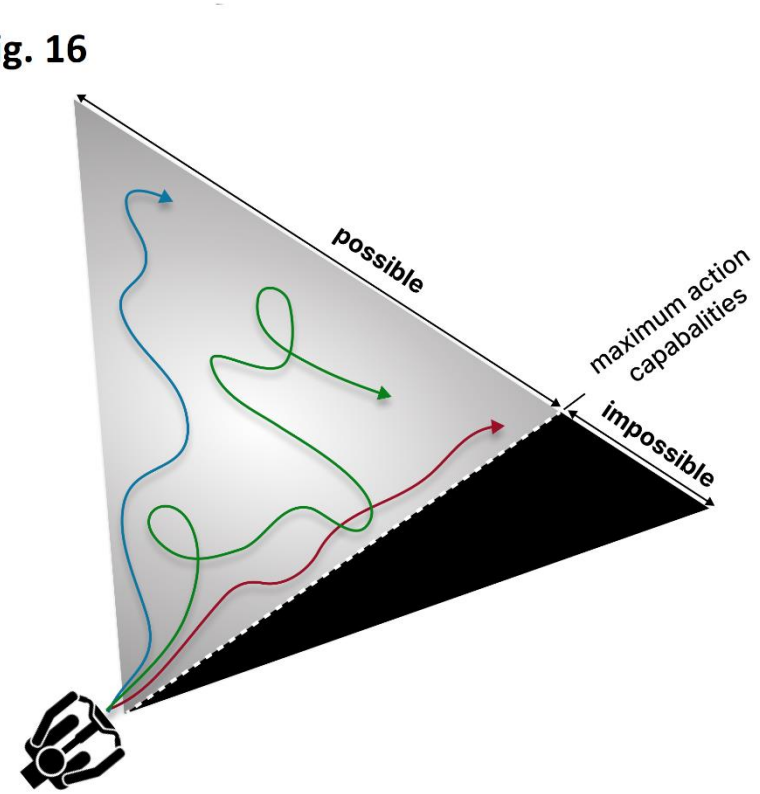


Figure 16: Different styles of control within the affordance-based approach. The maximum action capabilities boundary distinguishes possible (grey area) from impossible (black area) actions. Adopting a more aggressive control style involves acting closer to the boundary (red arrow), while a conservative style maintains distance from the boundary (blue arrow). Alternatively, performance may fluctuate within the field of possibilities, forming a new style (green arrow).

Source: Elaborated by the author. Based on "Guiding locomotion in complex, dynamic environments" by Fajen (2013).

To achieve task success, one might adopt a riskier style by acting close to the maximum action capabilities boundary (illustrated by the red arrow), or alternatively, a conservative style by staying far from the boundary (depicted by the blue arrow). It is also possible to alternate between near and far from the maximum boundary, forming a new style (as indicated by the green arrow). The maximum boundary determines the criteria for success or failure, representing a hard constraint that cannot be violated (FAJEN, 2005). While soft constraints, such as individual preferences and environmental or task-related factors, influence the action control style. Consequently, the affordance-based approach is seen as an enhancement of the information-based approach (HARRISON et al., 2016). This framework provides a fuller explanation while maintaining the ecological concept of direct perception.

I.2. Ecological representativity

Representative design consists of structuring experiments to include variables and conditions found in real-world situations (ARAÚJO et al., 2007; MILLER-DICKS et al., 2008). Thus, enhancing representativeness in experimental designs increases the ecological validity by incorporating factors that reflect the complexity of real-world scenarios.

Ecological studies (GIBSON, 1979; LEE, 1976; FAJEN, 2007) are often regarded as possessing greater ecological representativity compared to cognitivist experiments (RODRIGUES et al., 2020). Within the Gibsonian framework, understanding optical variables and affordances of the environment are seen as essential as analysing behaviour itself. Consequently, ecological studies are preferably conducted in real-world settings (i.e., in-situ experiments) rather than in laboratories. With the advancement of technology, many laboratory-based experiments utilize virtual environments, such as simulators, video games, and virtual reality. These tools afford safe environment and rigorously controlled conditions for researchers, which can be challenging to replicate in real-life contexts (BEULLENS et al., 2011; CICERI; RUSCIO, 2014; ROGERS et al., 2005). Chapters 2, 3, and 4 detail studies conducted using driving simulators, where we examined the visual and motor behaviour of different vulnerable drivers, including anxious drivers and drivers with Parkinson's disease. For instance, Chapter 2 reveals an increased number of collisions when drivers performed under high-anxiety conditions compared to low-anxiety conditions. Conducting such a study in a real-world urban traffic environment would be impractical due to the heightened accident risks. However, from a representativity perspective, simulators do not fully replicate the complexity and dynamics of real traffic environments. Discrepancies in gaze behaviour between virtual laboratory environments and in-situ experiments, as evidenced in studies by DICKS et al. (2010) and ZEUWTS et al. (2016), highlight this challenge. In virtual environments, individuals may experience high visual fidelity, yet they often miss the direct perception-action coupling (i.e., action-scaled information) (VAN DER KAMP et al., 2018). It is crucial to emphasize that representative design does not necessitate exact replication of real-world environments; rather, it underscores the preservation of critical aspects such as perception-action coupling. Thus, adopting an ecological approach does not imply abandoning laboratory research; instead, it involves aligning laboratory settings with the complexity of real-world environments. As GIBSON advised, “The laboratory must be like life!” (GIBSON, 1979, p.3). Both in-situ and in-lab experiments can serve as valuable methods for investigating visually guided actions in traffic research. However, due to their greater representativity and ecological validity, in-situ experiments are preferred when focusing on visually guided actions in traffic navigation (see review by LAPPI, 2022).

In summary, Gibson's ecological theory (1979) provides alternatives guides to discovery for investigating visually guided actions in traffic navigation. Within this framework, the affordance-based approach offers a comprehensive perspective by coupling the perception of affordances and action control. In the subsequent chapters, 5 and 6, I delve into the exploration of visually guided actions within the affordance-based approach. Pioneering studies on affordance-based control have utilized virtual environments (FAJEN, 2005a, 2005c, 2007). I advance this research by adopting a more representative approach, investigating the visual control of braking in in-situ cycling experiments. Despite cyclists being active participants in urban traffic, few studies have examined their perceptual-motor behaviour (VANSTEENKISTE et al., 2013, 2014; ZEUWTS et al., 2016). Using in-situ experiments, we offer empirical evidence examining the utility of the affordance-based control approach.

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Chapter 5.

Affordance-based control of braking in cycling: experience reveals differences in the style of control

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Abstract

We investigated whether in an in-situ collision avoidance experiment cyclists regulate braking by adopting an affordance-based control strategy. Within an affordance-based control strategy for braking, deceleration is controlled relative to the maximum achievable deceleration rather than by nulling out deviations from ideal deceleration, and potentially allowing for different braking styles. Twenty active- and eighteen inactive-cyclists were asked to cycle on a straight path in an indoor gym and to stop as close as possible in front of a stationary obstacle. Maximum achievable deceleration was manipulated by loading the bike: no-load, load-5kg, and load-10kg. Two approach distances were used to vary cycling speed. Participants in both groups stopped farther from the obstacle when approaching with long- than short-initial distance conditions. No systematic effects of loading on braking performance and control were found across the two groups. However, both groups did increase the magnitude of brake adjustments as ideal deceleration increased and got closer to the action boundary, even when current deceleration approached the ideal deceleration. This indicates that participants adopted an affordance-based control strategy for braking. Two braking styles were identified: an aggressive style, characterised by a late braking onset and a high, steep peak in ideal deceleration, and a conservative style, characterised by an early braking onset and gradual, linear increase in ideal deceleration. The aggressive braking style was more prevalent among the active-cyclists. We suggest that the braking styles emerge from differences in calibration between information and action. The novelty of our work lies in confirming that cyclists adopt an affordance-based control strategy in an in-situ experiment and in demonstrating and explicating how affordance-based control can incorporate the emergence of different styles of braking.

Keywords: affordance-based, visually guided braking, cycling, styles of control, scaling.

5.1. Introduction

The proposal that perceived affordances underpin movement control has gained increasing attention in empirical studies grounded within the ecological approach to perception and action (BLAU; WAGMAN, 2022; DICKS et al., 2010; FAJEN, 2005c, 2005a, 2007; POSTMA et al., 2017, 2018; SMITH; PEPPING, 2010; VAN ANDEL et al., 2017; VAN DER KAMP et al., 2018; VAN HOF et al., 2008; WARREN, 1984; WITHAGEN; MICHAELS, 2005; ZHENG et al., 2021, 2022). Affordances are the possibilities for action that emerge within the relationship between an actor and its immediate surroundings (GIBSON, 1979; STOFFREGEN, 2000; WARREN, 1984). For instance, when approaching an obstacle, a cyclist must perceive whether it is (still) possible to decelerate and stop in time. They will stop safely if they control braking such that the perception of stop-ability is sustained, underlining that the perception of affordances is grounded in the individual's action capabilities. In braking, this refers to the capability to decelerate sufficiently strong to bring a car or bike to a stop (FAJEN, 2005b, 2007). These capabilities for braking are not only determined by individual constraints (e.g., muscle power and fatigue, body weight, mood), but also by vehicle (e.g., the gain of the brakes, vehicle weight, load) and environmental constraints (e.g., weather conditions, slipperiness of the road) (SKRUCANY et al., 2020; VAN ANDEL et al., 2017). When braking capabilities are reduced, for instance when carrying an additional load on a bike, more time is needed to stop with the same braking strength, and the cyclist must initiate braking earlier and/or brake more firmly. However, if maximum braking capability is insufficient to achieve the required deceleration, then safe stopping is no longer possible. The perception of the affordance of stop-ability cannot be maintained any longer and the cyclist may opt to swerve out to avoid the obstacle (or brace for impact).

Researchers within the ecological approach have examined what and how information controls an unfolding action. This information-based control describes the lawful relation between information and movement (ANDERSEN et al., 1999; LEE, 1976; MICHAELS; OUDEJANS, 1992; SAVELSBERGH et al., 1991; VAN DER KAMP et al., 1999), including the (visual) control of braking, especially evoking error-nulling control strategies (e.g., tau-dot model [LEE, 1976; YILMAZ; WARREN, 1995], constant deceleration model [ANDERSEN et al., 1999]). For example, LEE (1976) mathematically demonstrated that the optical variable tau, defined as the inverse of the rate of change of the optical angle as the observer approaches a stationary obstacle (LEE, 1976), directly specifies the (momentary) remaining time until collision (i.e., time-to-contact) (for a more detailed description, see Appendix A). In fact, Lee proposed the constant tau-dot strategy, which holds that the ideal rate of deceleration to avoid a collision (i.e., the rate of deceleration that will bring the observer to a stop at the intended location without any additional braking adjustments needed) is achieved by holding the rate of change of tau, namely tau-dot, constant at the margin value of -0.5. Hence, when tau-dot is -0.5 the vehicle will stop in time, while when tau-dot deviates from this margin, adjustments in braking are required to cancel-out or 'null' the deviation. In this case, drivers must increase deceleration when tau-dot is smaller than -0.5 and decrease deceleration when tau-dot is larger than -0.5. Indeed, braking patterns that are consistent with the constant tau-dot strategy have been observed in virtual environments (ANDERSEN et al., 1999; ROGERS et al., 2005; VAN DER MEER et al., 2013; YILMAZ; WARREN, 1995), but also in-situ braking for car driving (ROCK et al., 2006) and bicycling (RODRIGUES et al., 2006, 2012). RODRIGUES and

colleagues (2006) asked cyclists to accelerate a bicycle until they entered a zone at 14 m from an obstacle, in which they were free to start braking to avoid collision with an obstacle. Participants performed the task within three self-propelled velocity conditions (high, medium, and low) and the results demonstrated that participants accomplished the task by holding tau-dot constant at -0.54, -0.54, and –0.55 in the three velocity conditions, respectively. RODRIGUES and colleagues (2012) also found that with curvilinear trajectories tau-dot was significantly unaltered and held at approximately -0.5, irrespective of velocity. These results provide strong support for cyclists using the constant tau-dot strategy for braking regulation. Yet, although empirically robust, FAJEN (2005, 2007b) argued that information-based control is limited in explicating how actors control their actions (see also HARRISON et al., 2016). Principally, it does not inform whether the actor can successfully achieve the task requirements. For example, the tau-dot specifies what needs to be done (i.e., increase or decrease deceleration), but not if it can be done (FAJEN, 2005b, 2007). This means that if the rate of deceleration needed for successful braking exceeds the maximal achievable deceleration, then it would be impossible to stop in time, but this cannot be known by an actor using a tau-dot strategy. Because in the tau-dot strategy the use of information is not scaled to action, this strategy (like other error-nulling strategies) remains mute on whether it is possible to stop in time.

Consequently, FAJEN (2005b, 2005c, 2005a, 2007) proposed the affordance-based control strategy. This strategy holds that information that controls action is scaled to the actor's capabilities, that is, to what an actor can maximally achieve, or their action boundaries. In braking, for example, the maximum achievable deceleration defines the boundary that separates the action of stopping safely from possible to impossible. To safely stop, the drivers must make brake adjustments so that the required deceleration does not exceed the maximum achievable deceleration (FAJEN, 2005c, 2005a, 2007, 2008). In other words, the driver must brake in such a way that the perception of stop-ability is sustained. Therefore, the perceived required deceleration is specified in units of maximum deceleration (FAJEN, 2007). In fact, braking adjustments are only (or especially) needed if the required or ideal deceleration threatens to get close or exceed the maximum achievable deceleration, rather than when it diverges from the current deceleration as per error-nulling strategy (FAJEN, 2005a, 2007) (See Appendix B for a more detailed description). To test both affordance-based control and error-nulling strategies, Fajen had drivers stopping a vehicle at a stop sign in a series of experiments in a simulated environment (FAJEN, 2005c, 2005a, 2007, 2008). Participants controlled car braking by pulling a joystick from the centre position, so that deceleration proportionally increased the further the joystick was pulled away from the centre position (FAJEN, 2005c, 2005a). FAJEN (2005c) manipulated drivers' braking capabilities by varying the strength of the brake across groups. That is, the same amount of joystick displacement resulted in different decelerations, creating a weak-brake (maximum deceleration of 5 m/s^2), a medium-brake (maximum deceleration of 7 m/s^2), and a strong-brake group (maximum deceleration of 9 m/s^2). FAJEN (2005c) reasoned that changes in action control following manipulation in action capabilities can only be explained by affordance-based control, and not by the error-nulling models. He reported that the mean ideal deceleration at braking onset was lower for the weak-brake group (i.e., they started adjusting earlier) compared to the medium-brake and strong-brake groups. However, when plotting the ideal deceleration (i.e., the constant deceleration

required to exactly stop at an obstacle) at braking onset in units of maximum deceleration (i.e., % of Dmax), group differences were absent, indicating that control was indeed scaled to action capability (FAJEN, 2005c). Additionally, FAJEN (2005a) analysed the occurrence of brake adjustments for intervals when the difference between current and ideal deceleration was close to zero (i.e., between – 1.0 and 1.0 m/s²). In these intervals, which have tau-dot values of approximately –0.5, a tau-dot strategy would not expect any brake adjustments, because errors are already nulled. However, drivers were observed to still make brake adjustments and were more likely to increase brake pressure when the ideal deceleration got closer to the maximum deceleration (i.e., ~90% of the brake adjustments resulted in increases in deceleration) than when ideal deceleration was close to zero (FAJEN, 2005a). This indicates that brake adjustments were made to ensure that ideal deceleration did not exceed the maximum achievable deceleration, also when there was no difference between current and ideal deceleration (FAJEN, 2005a). FAJEN concluded that drivers take into account their action capabilities and, therefore, control their action based on perceived affordances (FAJEN, 2005c, 2005a, 2007, 2008).

Perhaps somewhat paradoxically, the empirical studies on the affordance-based control of braking have all been conducted in virtual environments (FAJEN, 2005c, 2005a, 2007, 2008). From the perspective of ecological psychology, from which the concept of affordance originates (GIBSON, 1979), a virtual environment is potentially insufficiently representative for the dynamical and reciprocal actor-environment relation defining everyday actions. For instance, there are no physical consequences of collision in a virtual environment, which may affect when drivers start making brake adjustments when approaching their action boundaries. And although optical information in virtual environments nowadays has high fidelity, non-optical information associated with inertia is missing. This may be especially critical for calibrating (i.e., adapting to internal or external changes) when action capabilities change. Hence, we aimed to test Fajen's affordance-based control of braking in an in-situ braking experiment, and specifically examined if cyclists with different levels of experience take their action capabilities into account when braking to stop at an obstacle (FAJEN, 2005c, 2005a, 2007, 2008). In the present study, we manipulated the action capabilities, as defined across the person-bicycle system, by adding, unknown to the participants, additional load to the bike. We sought evidence whether adaptive brake adjustments would be made relative to maximum achievable decelerations or to nulling differences with ideal deceleration. In addition, we also addressed possibly different styles of braking. For example, on a relaxed weekend trip cyclists may opt to brake early and very gradually, while when in a rush they may start braking late and very forcefully. The affordance-based control approach potentially allows for accommodating of these intra- and inter-individual variations in the control of braking. FAJEN (2005b) wrote, "In braking, for example, one could adopt a conservative style and minimize collisions by making adjustments to keep the ideal deceleration near the bottom of the safe region, close to zero. Or one could adopt a more aggressive style to minimize approach time by allowing the ideal deceleration to draw near the top of the safe region, close to maximum deceleration" (p. 726). The safe region here represents the field of solutions within the action boundaries, that is, between zero or minimum and maximum deceleration. All trajectories within these action boundaries are adequate for safe stopping (FAJEN, 2005b). That means, although actors use the same general control strategy (i.e., keeping the ideal deceleration below maximum

deceleration), they can still show different styles of control based on individual or contextual specific requirements (e.g., mood, likelihood of being fined etc.). In this respect, in in-situ braking, a relatively conservative style of braking may be expected due to a real risk of physical damage following a collision compared to virtual braking. The differences in style may also relate to skill or experience. That is, experienced individuals have been shown to have greater sensitivity to their action boundaries (DICKS et al., 2010; HIGUCHI et al., 2011; SEIFERT et al., 2021), which would allow them to explore different styles of control. For example, ZHENG et al. (2021, see also DICKS et al., 2010) showed that both less and high skilled football goalkeepers took their action capabilities (i.e., the minimum time they needed to reach the ball) into account when trying to stop a penalty kick, but high skilled goalkeepers acted closer to their action boundary (ZHENG et al., 2021). Analogously, skill level or degree of experience may also shape the chosen braking trajectories within the safe region, resulting in different styles of braking.

The main objective of this study was to investigate whether the control of braking of cyclists in in-situ environments is affordance-based. We assessed this through the utilization of two distinct methods. First, we aimed to manipulate braking capabilities by adding loads to the bicycle, with the heaviest load reducing maximum deceleration the most and consequently increasing the time required to stop. We anticipated lower Dideal at braking onset (i.e., earlier braking onset) in the +10kg condition compared to the +5kg and no-load conditions. However, when subsequently expressing Dideal at braking onset in units of maximum deceleration (i.e., % of obsDmax), load-related differences would disappear, corroborating FAJEN's findings (2005c). Second, we aimed to examine if brake adjustments still occurred when current and ideal deceleration were zero or close to zero (i.e., when deceleration error is already nulled). If participants use an error-nulling strategy, no further brake adjustments are expected (LEE, 1976). By contrast, if participants use affordance-based control, brake adjustments may still occur and would increase in magnitude as ideal deceleration increases and gets closer to the action boundary (FAJEN, 2005). As a secondary objective, we explored if level of experience influences the style of braking. We expected that active-cyclists would feel safer or more in control and thus be more likely to adopt an aggressive style of braking, performing closer to their maximum action capabilities, compared to inactive-cyclists.

5.2. Method

Participants

An a priori power analysis (G*Power 3.1.9.7) for a repeated measures analysis of variance (RM-ANOVA) indicated a minimum sample size of thirty-six subjects (i.e., $\beta = .80$, $\alpha = .05$, effect size $f = .20$). Forty adults (16 females) who voluntarily participated in this study were recruited from the city of Bauru, Brazil. Before the study, they had completed a questionnaire designed to estimate cycling experience (Q1 - How old were you when you learned to ride a bike?; Q2 – How many days a week do you typically cycle in the city?; Q3 – How many kilometres do you typically cycle per day?) and physical fitness level (Q1 – Do you practice any aerobic physical activities, except cycling?; Q2 – How often do you practice it weekly?) within the six months preceding the experiment. Participants were eligible to take part in the study as active-cyclists (n=20) if they reported experience in urban cycling (i.e.,

using a bicycle as a way of commuting through the city) at least three times a week, with weekly and annually distances of at least 20 and 500 km, respectively (Lehtonen, et. al., 2016). To quantify the total annual distance pedalled (d_t), the following equation was adopted based on the self-reported data collected:

$$d_t = [(Q_2 \times Q_3) \times 52] \quad (5)$$

where Q_2 is the weekly cycling rate and Q_3 is the daily mileage, and 52 the number of weeks per year. The inactive-cyclists group (n=20) was composed of participants who reported the ability to ride a bicycle; however, they had not practiced urban cycling for at least the last 10 years. The participants in this group were physically active and engaged in some type of moderate/intense aerobic physical activity, except cycling, at least three times a week (Dantas et al., 2009; Lehtonen et al., 2016). Data from one active-cyclist and two inactive-cyclists were missing due to equipment failure, hence the final number of participants included in the data analysis was 37. Table 6 presents their characteristics. All participants had normal or corrected-to-normal vision (i.e., score range of 20/20 to 20/30 on the Snellen visual acuity test), absence of sensorimotor impairments, neurotypical system, and were within the height and weight ranges of 160 – 180 cm and 60 – 80 kg, respectively. The protocol was approved by the São Paulo State University Ethical Committee (CAAE: #08411519.1.0000.5398) and conducted according to the principles of the Declaration of Helsinki. Participants signed informed consent prior to the start of the experiment.

Table 6. Means (SDs) for characteristics of the participants (n=37) by experimental group.

	Active-cyclists (n=19)	Inactive-cyclists (n=18)
Age (years)	29.42 (6.28)	29.50 (3.83)
Weight (kg)	74.60 (7.10)	77.10 (10.10)
Height (m)	174.26 (5.72)	179.78 (5.96)
Weekly distance pedaled (km)	46.42 (17.47)	N/A
Annual distance pedaled (km)	2,244.84 (884.64)	N/A

N/A refers to not applicable.

Apparatus

A South Hunter GT 29" (South Bike), 21 gears, frame size 17 and mechanical disc-brake system was used in this study. The frame size was suitable for the height of all participants and the saddle was individually adjusted so that participants could comfortably reach the ground with their toes while sitting on the bicycle. The braking task was recorded using a GoPro camera (Hero 3) at a sampling rate of 60 Hz and resolution of 1920x1080. A white spherical marker was attached to the head tube of the bicycle for motion tracking purposes (Figure 17a). Data from GoPro videos was used to calculate the rate of deceleration over time. To assess brake adjustments, Hall-effect sensors (US1881/U18) were attached on the handlebar grips and magnets fixed to the brake levers (right-brake and left-brake). These sensors are commonly

used to determine the position of an object based on a magnetic field (Ramsdem, 2011; Jezný & Čurilla, 2013; Saha et al., 2017). The calibration of the Hall-effect sensors involved three steps: i) positioning, verify the position and orientation of the sensors and the magnets on the bicycle; ii) baseline, one-minute baseline data recording without any brake lever interference; iii) testing, one-minute test recording, starting with both brakes fully released, followed by fully pressing the right brake, releasing it, and next fully pressing the left brake, releasing it. The magnetic flux exhibited a direct proportionality to the displacement of the brake levers, ranging from 210 GAUSS (fully released) to 580 GAUSS (fully pressed). After confirming these values, the data collection was initiated. The brake sensors were connected to an Arduino-UNO (R3) system installed in a black box fixed at the centre of the handlebar (Figure 17a). By using analog-to-digital feature, the Arduino converted the magnetic flux voltage to a numerical output and transmitted it to a smartphone (SM-A305GT, Android 11) via an USB cable, where the output was stored in a Serial USB Terminal app (Kai Morich, version 1.45). Data from the magnetic sensors were used to provide data regarding participants' control of the brakes (i.e., onset and adjustments) during the test.

Procedure and Design

The data collection took place in the sports hall of the Department of Physical Education at São Paulo State University, Bauru, Brazil. A linear cycle path (1m-width, 37m-long) was demarcated on the floor by an adhesive yellow/black tape (Figure 17b). The cycle path was divided into two zones: the approaching zone, from the initial distances to the beginning of a black mat; and the stopping zone, beginning at the black mat until the obstacle at the end of the path. Two initial distances were used to manipulate cycling speed (Rodrigues et. al., 2006): i) short-initial-distance, initial distance at 21.6m from the obstacle; and ii) long-initial-distance, initial distance at 37m from the obstacle. The differences in maximum velocity were aimed at varying task demands, that is, a higher speed would result in less time available to stop. To avoid accidents caused by skidding during braking, a black anti-slip mat (2mm-thick, 1m-width, 14m-long) was placed in the stopping zone. The obstacle (0.81m-height, 0.05m-width, 0.15m-long) placed at the end of the cycle path, blocking the path, was made of foam. Prior to the beginning of the braking test, participants had 5 minutes to familiarize with the bicycle, experimental setting, and task instructions[4]. Participants were asked to accelerate the bicycle as fast as possible until they reached the stopping zone, from which they were free to initiate braking, aiming to stop as close as possible to the obstacle and to avoid the collision. To synchronize the brake sensors with the video recordings, participants were asked to start each trial with fully-pressed brakes and, on the experimenter's command, release the brake levers as fast as possible and immediately start accelerating the bike. Bicycle weight was manipulated to change maximum deceleration (Fajen, 2005c, 2005a; Skrucany et al., 2020). Loads of 5kg and 10kg were added to the bicycle frame (i.e., inserted in a cargo bag attached to the frame (Figure 17a) to create the following load conditions: i) no-load, the bicycle without additional loads; ii) 5kg-load, the bicycle with the addition of 5kg; iii) 10kg-load, the bicycle with the addition of 10kg. In each load condition block, four trials were performed in short-initial-

[4] Participants also wore eye tracking glasses (Mobile Eye-5 glasses, ASL) during the experiment. The results from gaze analysis, however, will be discussed in a subsequent paper.

distance and four in long-initial-distance condition, eight trials per block, totalizing 24 trials. The order of blocks and trials were randomized. A three-minute interval between the blocks was given to avoid participants from becoming physically fatigued. The bicycle loading manipulation was performed so that the participant did not notice it. No participant reported awareness of a change in the bicycle weight during data collection.

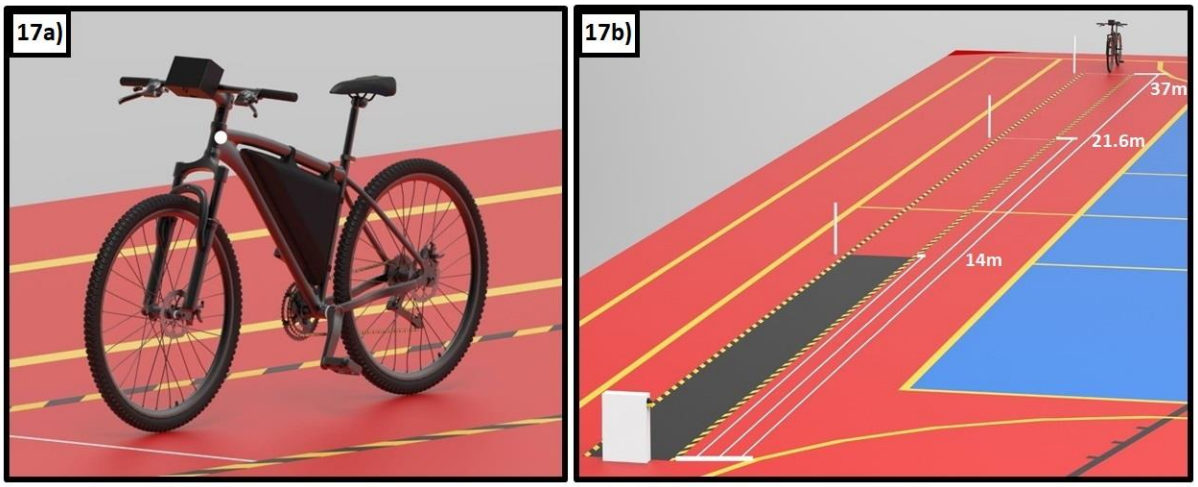


Figure 17: a) computer-generated image of the experimental bicycle with the cargo bag attached to the frame, the Arduino controller box at the handlebar, and the white spherical marker for motion tracking purposes; b) computer-generated image representing the approaching (red floor) and stopping (black mat) zones of the cycle path and the foam obstacle (white cuboid). Initial distances placed at 21.6m and 37m to the obstacle were used for short-initial-distance and long-initial-distance conditions, respectively.

Data analysis

Prior to data processing, GoPro radial distortion was corrected from the videos using algorithms based on the Hough transformation (Santana-Cedrés et al., 2016; Vieira et al., 2017). The software is a command-line tool, running in Ubuntu Linux (18.04.3 LTS), that estimates the lens distortion model from a single frame of the original video and creates its undistorted version. The trajectory of the bicycle was tracked frame-by-frame using the Kinovea software (version 0.9.1). Prior to data collection, we positioned two cones to delineate the starting and ending points of the cycle path. The initial cone was aligned so that its basis's upper right corner (viewed from the top) precisely coincided with the starting line, while the final cone was placed at the end line with its upper left corner (viewed from the top). The two corners precisely denoted a distance of 37 meters. A one-minute video recorded these cones as spatial reference points for calibration in the subsequent tracking analysis using Kinovea software. Following the data collection phase, the cones were removed from the cycle path to carry out the braking test. Post-collection, the calibration involved marking the distance between the two cones to set the video scale, ensuring accurate measurements corresponding to real-world dimensions. This process was repeated for each video before initiating any tracking analysis. The digitized coordinates were passed through a low-pass filter (second-order Butterworth) to remove noise (Winter, 2009). Total horizontal displacement of the

bicycle was computed for each participant in each trial and exported as tabular data in CSV format. Algorithm collections for signal processing and variables calculation were developed using MATLAB software (The MathWorks Inc., USA, version R2018b). The following dependent variables were derived: Speed manipulation check: maximum velocity (m/s) was calculated by identifying the highest peak on the velocity curve across the trial. Braking performance: first, the number of trials with a collision with the obstacle (soft touches were also included) was counted in each condition. Second, the final stopping distance from the obstacle was determined by taking the distance (m) between the front edge of the front wheel and the obstacle in the final frame (i.e., bicycle velocity reached zero). The mean and SD final stopping distance (m) served as dependent variables.

Control strategy: the analysis of braking and the regulation of deceleration was based on Fajen's studies (2005a; 2005c). From the total horizontal displacement, we derived several parameters for every frame, including the distance from the obstacle (Z), the velocity (V) and the deceleration (D) of the bicycle. Moreover, for each frame, the following variables were also calculated: the momentary deceleration, that is the current deceleration (Dcurrent) and the ideal deceleration (Dideal), that is the constant rate of deceleration required to exactly stop at the obstacle without making any further adjustments. The observed maximum deceleration (obsDmax) was measured by taking the maximum value of Dcurrent in each bicycle load condition. Brake adjustments were identified when the distance between the magnets (brake levers) and hall-effect sensors (handlebar grips) changed. The magnetic flux was directly proportional to the brake levers displacements, ranging from 210 GAUSS (fully released brakes) to 580 GAUSS (fully pressed brakes). Brake displacement data was then normalized, with 0 attributed to fully released brakes and 1 indicating fully-pressed brakes (or maximum brake displacement). Brake adjustments were identified, using the MATLAB's function 'findchangepts', by the mean and the slope of the signal changing abruptly with a minimum residual error increase of 0.1 (i.e., 10% of maximum brake displacement as in Fajen, 2008). Brake adjustments that resulted in increases in deceleration (brake displacement > 0.1), were computed as 'positive' adjustments; decreases (brake displacement < -0.1) and holds (0.1 < brake displacement > -0.1) in deceleration were counted as 'negative' and 'no' adjustments, respectively. Only 'positive' brake adjustments were included in the subsequent analyses (Fajen, 2005a). Braking onset (s) was defined as the moment of the first brake adjustment. We identified the value of Dideal at braking onset (measured in m/s^2). To examine whether control was based on affordances, we also expressed Dideal at brake onset in units of observed maximum deceleration (% obsDmax). Each brake adjustment occurs at a specific value of Dideal and to examine the relation between magnitude of brake adjustment and Dideal, brake adjustments were grouped into four equally spaced bins (or intervals) of Dideal (m/s^2). The bins ranged from zero to the maximum Dideal. Following Fajen's study (Fajen, 2005a), we only considered Dideal bins in which the deceleration error was between -14.28 % and 14.28 % of obsDmax[5]. Magnitude of brake adjustments for each Dideal bin was calculated.

[5] Deceleration error is the difference between Dideal and Dcurrent at each instant. In the article by Fajen (2005a), the deceleration error was considered 'nulled' whenever it remained between –1.0 and 1.0 m/s^2, that is, 14.28% of the maximum deceleration used (7 m/s^2). As the range of deceleration of a bicycle is substantially smaller than that of cars (Fajen's protocol), the relative deceleration error was adopted in the present study.

Styles of braking: Initial perusal of the data showed that participants indeed adopted different styles of braking (Figure 20a). We classified each individual trial into one of three styles of braking control based on the unfolding of Dideal and Dcurrent during the trial. The three styles were identified according to the shape of Dideal and Dcurrent curves as: i) aggressive style, the Dideal curve shows a skewed parabolic shape and its peak occurs near the end of the trial and Dcurrent shows a higher peak just after the Dideal peak (i.e., active braking is initiated late and high decelerations are achieved briefly before the stop); ii) conservative style, the Dideal curve grows linearly and flattens near the end of the trial, and Dcurrent shows frequent, small local peaks (i.e., gradual braking is initiated early and a moderate rate of deceleration is maintained until the stop); iii) other, mostly Dideal and Dcurrent show an early peak with multiple local peaks for Dcurrent until the end of the trial (i.e., braking is initiated earlier but with high variations, resulting in Dideal oscillating erratically). Based on the above description two raters (GG, JvdK) independently categorized each trial for each participant. Cohen's Kappa reliability test was performed to measure the level of agreement between two raters in classifying the style of braking. In the initial round, Cohen's κ indicated a moderate agreement between the two raters, $\kappa = .730$, $p < .001$. To further increase agreement, the two raters reviewed the plots together to reach an agreement on the remaining discrepancies. Next, categorization was further verified by calculating r^2 values for fitting polynomial curves of 1st, 2nd and 3rd order of the Dideal. If the r^2 for 2nd order polynomial was closer to the r^2 for the 3rd order polynomial than to r^2 for the 1st order polynomial, the trial was categorized as an aggressive style; if the r^2 value for the 2nd order polynomial was closer to the r^2 on the 1st order polynomial then the trial was categorized as a conservative braking style. In doing so, the categories conservative and other were combined into one conservative category. There was a strong agreement between the classification by the two raters and the classification using the polynomial fitting procedure, $\kappa = .949$, $p < .001$. Frequency distribution of braking styles was computed across conditions for all participants. To provide a more comprehensive characterization of the styles, the dependent variables observed maximum deceleration and braking onset were used.

Statistical analysis

The Shapiro Wilk normality test was conducted on all dependent variables. For the parametric variables, group (active-cyclists, inactive-cyclists) by bicycle load (no-load, 5kg-load, 10kg-load) by initial distance (short-initial-distance, long-initial-distance) analyses of variance with repeated measures (RM-ANOVA) on the last two factors were conducted. In case the assumption of normal distribution was violated, a generalized estimating equation (GEE) method was conducted under same factorial effects. Speed manipulation check: maximum velocity was submitted to a GEE analysis. Braking performance: percentage of collisions, final stopping distance, and SD final stopping distance were submitted to GEE analyses. Control strategy: observed maximum deceleration was submitted to an RM-ANOVA. Dideal at braking onset (in m/s^2) and Dideal at braking onset (in % obsDmax) were submitted to GEE analyses. In addition, multiple linear regression analyses were conducted for each group separately to examine whether the magnitude of brake adjustments was predicted by ideal deceleration and/or load conditions. Styles of braking: Chi-square, and McNemar's and Cochran's Q tests were conducted to examine whether the distribution of braking styles

differed by group, bicycle load, and cycling speed and/or interactions between the factors, respectively. Additionally, braking onset and observed maximum deceleration were submitted to GEE analyses with styles of braking (aggressive style, conservative style) as a factor. Statistical analyses were run using SPSS Statistics (17.0.1). Tukey Honestly Significant Difference tests and Greenhouse-Geisser degrees of freedom adjustments were conducted when necessary. The value alpha was set at .05. Effect sizes were calculated using Partial Eta Squared with 0.02 or less, 0.06, and 0.14 or more, representing small, medium, and large effect sizes, respectively (Cohen, 1988).

5.3. Results

Speed manipulation check

For the maximum velocity, GEE revealed a main effect of load ($\chi^2 = 67.031$, $p < .001$) and initial distance ($\chi^2 = 379.334$, $p < .001$), indicating that participants indeed reached a greater maximum velocity in the long-initial-distance condition (M = 6.11; SE = .180 m/s) than in the short-initial-distance condition (M = 4.09; SE = .083 m/s). In addition, participants pedalled faster in no-load (M = 5.198; SE = .131 m/s) than in the 5kg-load (M = 5.11; SE = .132 m/s) and 10kg-load conditions (M = 5.00; SE = .129 m/s). No effects for group were present.

Braking performance

Participants of both groups did almost always manage to stop in time, resulting in a low number of collisions that were independent of initial distance and load (Figure 18a). Yet, the GEE indicated a main effect of initial distance for final stopping distance ($\chi^2 = 52.673$, $p < .001$), indicating that participants stopped farther from the obstacle in the long-initial-distance than short-initial-distance condition (Figure 18b). Finally, for the SD final stopping distance, a main effect of group ($\chi^2 = 7.541$, $p = .006$) and an interaction between group, load, and initial distance ($\chi^2 = 6.191$, $p = .045$) were revealed. Post-hoc comparisons indicated that the inactive-cyclists group showed larger variability in the final stopping distance than the active-cyclist, but only in the 10kg-load short-initial-distance condition (Figure 18c).

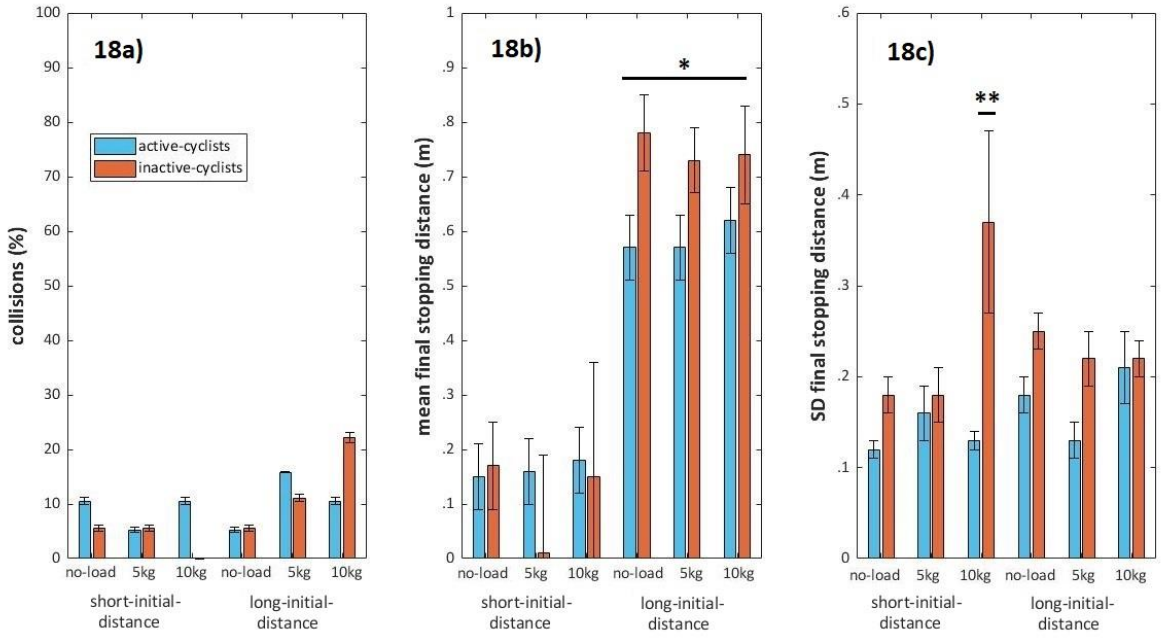


Figure 18: a) percentage of collisions, b) average final stopping distance and c) average within-subject SD final stopping distance across initial distance and load for active-cyclists (blue bars) and inactive-cyclists (red bars). *Significant main effect of initial distance; **Significant interaction between group, load, and initial distance.

Control strategy

Fig. 19a shows that loading the bicycle did not systematically decrease the observed maximum deceleration across the two groups. Instead, RM-ANOVA revealed main effects of initial distance, $F(1,35) = 70.067$, $p < .001$, $\eta p^2 = .667$, and an interaction between group, load and initial distance, $F(2,70) = 3.341$, $p = .050$, $\eta p^2 = .087$. Post-hoc comparisons indicated only differences in the observed maximum deceleration for the inactive-cyclists. In the short-initial-distance condition they showed higher observed maximum deceleration in the no-load condition than in the 5kg-load and 10kg-load conditions. Following Fajen (2005c), we then tested if Dideal at braking onset (in m/s^2) different depending on loading, and if so, whether these differences would disappear when scaling Dideal to maximum deceleration (in % obsDmax). No differences were found for both Dideal at braking onset (in m/s^2) and Dideal at braking onset (in % obsDmax) across load conditions.

We also examined if brake adjustments are relative to maximum deceleration or to null error from ideal deceleration. Accordingly, we analysed brake adjustments as a function of ideal deceleration only for intervals where the difference between current and ideal deceleration is approximately zero (and hence, no systematic brake adjustments are predicted from error-nulling models). The multiple linear regression revealed significant models for both the active-cyclists, $F(2,11) = 48.286$, $p < .001$, $R2 = .915$, and the inactive-cyclists, $F(2,11) = 48.796$, $P < .001$, $R2 = .916$. For both analyses, the magnitude of brake adjustments was significantly predicted by ideal deceleration, $p < .001$, but not by load conditions. The slopes of the regression line (Fig. 19b and 19c) were significantly steeper than zero for both the active-cyclists ($B=0.503$, $t = 9.826$, $p < 0.001$) and the inactive-cyclists ($B=0.401$, $t = 9.871$, $p <$

0.001), indicating that magnitude of brake adjustments depended on ideal deceleration, regardless of load condition.

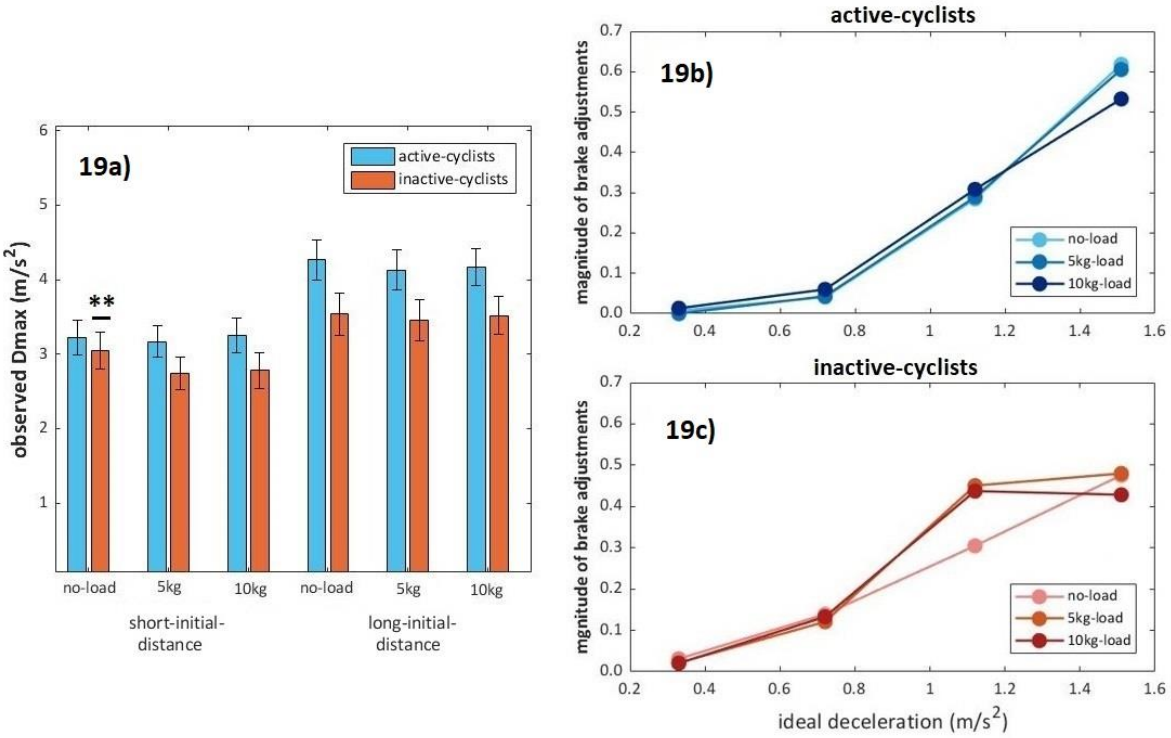


Figure 19: a) observed maximum deceleration across load and initial distance for active-cyclists (blue bars) and inactive-cyclists (red bars); b) magnitude of brake adjustments as a function of ideal deceleration by load conditions for active-cyclists; and c) for inactive-cyclists. All frames used in this analysis showed a deceleration error close to zero (or 'nulled').

Styles of braking

The frequency distribution of the aggressive and conservative styles of braking is showed in Fig. 20b. Chi-square analysis showed a significant association between the style of braking and group, χ^2 (1) = 22.42, p < .001. The odds ratio indicated that the proportion of aggressive style was 4.25 times higher among the active-cyclists compared to the inactive-cyclists. McNemar's and Cochran's tests were used to compare distribution of braking styles across initial distance and load conditions, respectively. McNemar's test revealed that there was no significant difference in the distribution of braking styles across the initial distance conditions, p = .332. Likewise, Cochran's Q test showed no significant difference in the distribution of braking styles between the load conditions, χ^2 (2) = 4.000, p = .135). GEE analysis confirmed significant differences in braking onset (χ^2 = 8.291, p = .004) and observed maximum deceleration (χ^2 = 45.059, p < .001) between the braking styles. The aggressive style was associated with later braking onset and reached higher observed maximum deceleration compared to the conservative brakers (Fig. 20c).

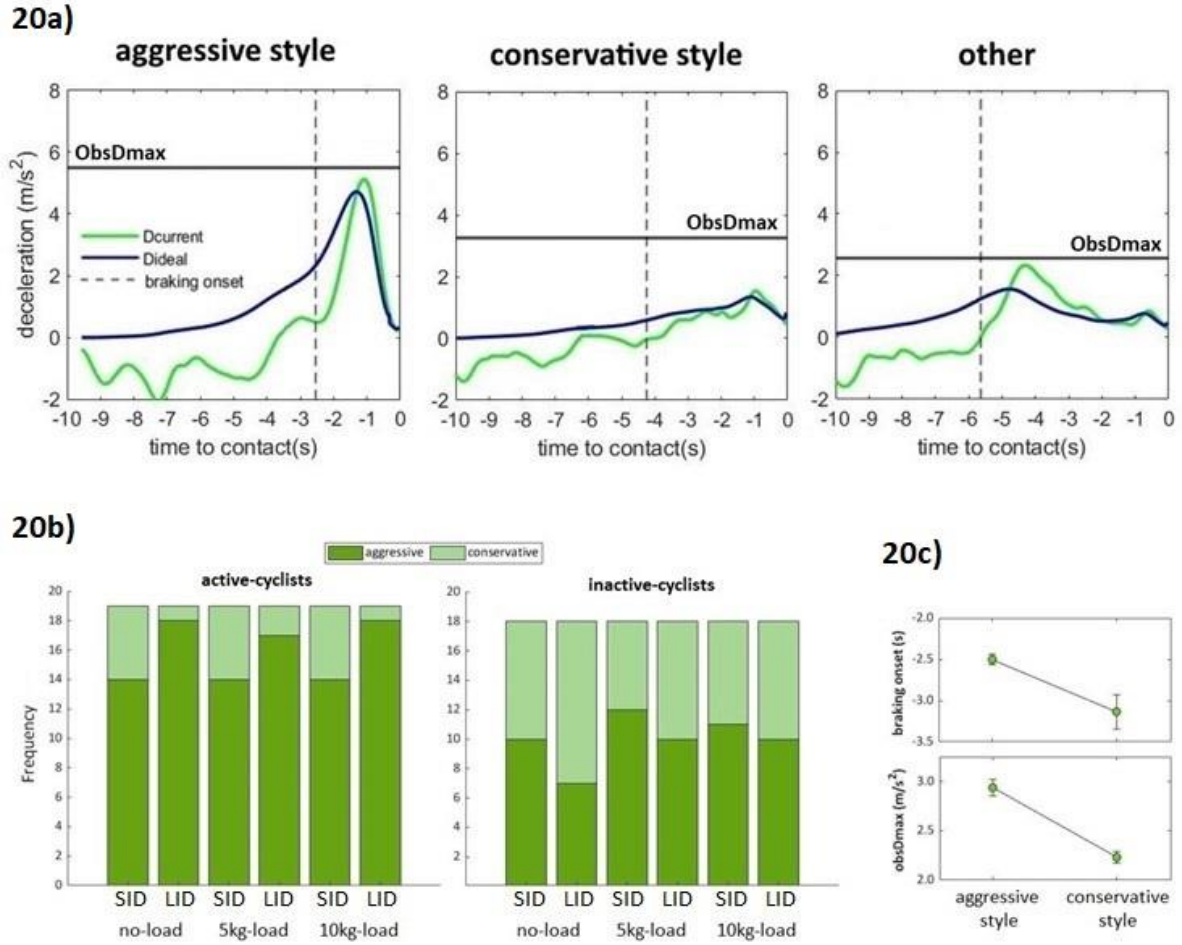


Figure 20: a) Styles of braking control: i) aggressive style, Dideal curve shows a skewed parabolic shape, with a late braking onset and a high and steep peak; ii) conservative style, Dideal curve grows linearly flat and low peak; and iii) other, early peak decelerations with multiple subsequent local peaks for Dideal and Dcurrent; b) Frequency of braking styles per group across load and initial distance conditions. c) braking onset and observed maximum deceleration (obsDmax) by styles of braking.

5.4. Discussion

This study investigated how active- and inactive-cyclists regulate brake adjustments to succeed in a collision avoidance task. We adapted the virtual braking protocol used by FAJEN (2005c, 2005a, 2008) to assess cyclists' behaviours in an in-situ experiment, that is, participants were asked to ride a conventional mountain bike in a gymnasium and stop as close as possible to an obstacle. Extra loads were added on the bicycle, to manipulate braking capabilities, in which a heavier bike was expected to reduce the maximum achievable deceleration. Task demands were manipulated by using different initial distances such that maximum velocity at braking onset and the time available to stop were varied. We found that participants stopped farther away in front of the obstacle when approaching with long-initial-distance compared to an approach with short-initial-distance, whilst no differences were found across load

conditions. Yet, both the inactive- and the active-cyclists were largely successful in following task instructions and showed equally low number of collisions, although the inactive cyclists did show a higher variability in stopping distance to the obstacle. We found partial evidence that both groups regulated braking in accordance with an affordance-based control strategy but achieved this using different styles of braking, irrespective of load condition.

Control strategy

First, to test the effects of changing action capabilities on brake adjustments in-situ, we added extra loads to the bike to change braking capabilities, with the heaviest load predicted to reduce the observed maximum deceleration the most. Yet, no evidence was forthcoming that loading the bicycle systematically decreases the observed maximum deceleration. Only for the inactive-cyclists in the short-initial-distance condition, the observed maximum deceleration was found to be higher in the no-load condition than in the 5kg-load and 10kg-load conditions. In addition, the results also did not confirm that cyclists would initiate braking at lower values of ideal deceleration (i.e., Dideal in m/s^2) with the extra load. We found no evidence that the current loading systematically affected participants' control of braking. Consequently, we were unable to test whether the differences in ideal deceleration would disappear when scaling to participants' action capabilities, that is, when expressed in maximum deceleration (i.e., Dideal in % obsDmax) as is predicted for affordance-based control (FAJEN, 2005c). A possible explanation for the lack of differences in loading may relate to the positioning of the loads on the bicycle. We added the loads of 5kg and 10kg in a cargo bag on the bicycle frame, close to the individual-bicycle centre of mass (Figure 17a). To prevent participants' awareness of the manipulation, the addition or removal of the loads to the bicycle were performed in a separate environment. Only 2 of the 37 participants reported that something changed on the bike, but they were unable to point out what exactly had changed. This demonstrates that participants remained largely unaware of the manipulation. However, placing the loads close to the individual-bicycle centre of mass may have reduced potential disturbances to the braking power. SKRUCANY, VRABEL and KAZIMIR (2020) found that adding front-loaded weight to a car significantly reduced braking power compared to centre- or rear-loaded weights. Nonetheless, we added 5kg and 10kg to the bicycle frame, representing approximately 5% to 15% of the individual-cycle total weight, respectively, while the loads SKRUCANY et al. (2020) ranged between 10% to 40% of the car's mass. Unlike SKRUCANY et al. (2020), we did not observe that the extra loads perturbed braking, indicating that future studies should consider both the positioning of loads and use heavier loads. Alternatively, braking on different slopes (e.g., uphill versus downhill) or under physical fatigue may be feasible protocols for empirical studies to investigate that braking in cycling is scaled to action capabilities as presumed in affordance-based control.

Second, to investigate whether cyclists use an affordance-based strategy to control braking, we also examined if brake adjustments occurred when the difference between current and ideal decelerations was close to zero (i.e., deceleration error is nulled) (FAJEN, 2005a). An error-nulling strategy anticipates no further brake adjustments if current acceleration equals or approaches ideal deceleration, while affordance-based control predicts increased magnitude of brake adjustments as ideal deceleration surges and (thus) gets closer to the action boundary. Indeed, the multiple linear regression analysis revealed that participants did increase the

magnitude of brake adjustments as the ideal deceleration increased (Fig. 19b and 19c), regardless of group and load condition. This corroborates previous findings (FAJEN, 2005c, 2005a) and provides evidence that participants adopted an affordance-based control strategy for braking regulation in cycling. That is, brake adjustments are scaled to action capabilities in such a way that ideal deceleration is kept within the action boundaries rather than to null the deceleration error (FAJEN, 2005c, 2005a, 2007). This is the first study to provide evidence that cyclists regulate braking in-situ by sustaining the perception of stop-ability. Previously, RODRIGUES and colleagues (RODRIGUES et al., 2006, 2012) found support for cyclists using an error-nulling strategy (i.e., the constant tau-dot) in collision avoidance braking. However, those studies did not capture how the use of tau-dot is grounded in the cyclists' action capability. This is a critical constraint for control of braking when studied from an ecological psychology approach (FAJEN, 2005c, 2005a, 2007, 2008). Yet, while FAJEN used virtual environments to show this for car driving, we extend this work to in-situ environments, in which the grounding of control in action (capabilities) is arguably much more precarious. In sum, even though the load manipulation was insufficiently effective to allow us to fully address the objectives of the study, we do find partial evidence that the control of braking is affordance-based. In particular, we demonstrate that systematic adjustments in magnitude of braking adjustments occurred, even when the system was in the ideal action state. Our results thus indicate that cyclists avoid collisions by making adaptive brake adjustments that keep ideal deceleration below the maximum achievable deceleration rather than nulling the deviation with ideal deceleration. Therefore, despite the absence of significant load-related effects on observed maximum deceleration and brake adjustments, the study provides initial evidence supporting participants' use of an affordance-based control strategy.

Styles of braking

Finally, we sought evidence whether cyclists would show different styles of control in an in-situ braking in cycling. Affordance-based control holds that the primary constraint on successful braking is to keep the ideal deceleration required to stop below the maximum deceleration. Within this constraint, however, different braking styles are still enabled. We expected that experience may invite different styles, with active-cyclists feeling safer and more in control, and thus more likely to adopt an aggressive style of braking, that is, performing closer to their maximum action capabilities, when compared to inactive-cyclists. Indeed, we identified two braking styles: an aggressive style, characterized by a late braking onset and a high, steep peak in ideal deceleration and a more conservative style, characterized by an early braking onset and a gradual, linear increase in ideal deceleration. The aggressive braking style was more prevalent among active-cyclists compared to inactive-cyclists. This result confirms our hypothesis that the more experienced individuals act closer to their action boundaries (DICKS et al., 2010; FAJEN, 2005b, 2007; HIGUCHI et al., 2011; SEIFERT et al., 2021; ZHENG et al., 2021). For example, ZHENG et al. (2020) showed that both less and high skilled football goalkeepers considered their action capabilities (i.e., the minimum time they needed to reach the ball) when trying to stop a penalty kick, but the high skilled goalkeepers acted closer to their action boundary. That is, they started the dive when the required velocity to reach the ball equaled the maximum dive velocity they could achieve, which translated in coordinating the dive onset with the moment the kicker's non-kicking leg landed next to the

ball (ZHENG et al., 2021; see also VAN DER KAMP et al., 2018). Possibly, experience or exposure enhances the sensitivity to the action boundaries, allowing them to act closer to the boundaries without going beyond them. We suggest that the different styles of braking reflect differences in the calibration between information and action (BINGHAM; PAGANO, 1998; FAJEN, 2005b, 2007). Figure 21 illustrates this reasoning (see also FAJEN, 2005c, and Figure 19b and 19c above). It shows the magnitude of brake adjustments as a function of ideal deceleration, with the latter being scaled to the observed maximum deceleration (% obsDmax) for the two braking styles. Because the brake adjustment is normalized (i.e., 0 representing fully released brakes and 1 indicating fully-pressed brakes), we can directly compare how the perceived ideal deceleration in units of maximum deceleration scales to the magnitude of brake adjustments in units of maximum brake displacement. Separate multiple linear regression analysis for each braking style confirmed that the magnitude of brake adjustment was significantly predicted by ideal deceleration in units of observed maximum deceleration, p's < .001. Importantly, the slope of the regression is found to be significantly larger for the more aggressive style compared to the conservative style, $t = -4.604$, $p < .001$. This indicates that perceived ideal deceleration has a stronger impact on the brake adjustments for the aggressive style of braking than for the conservative braking style, which points to a difference in calibration.

Fig. 21

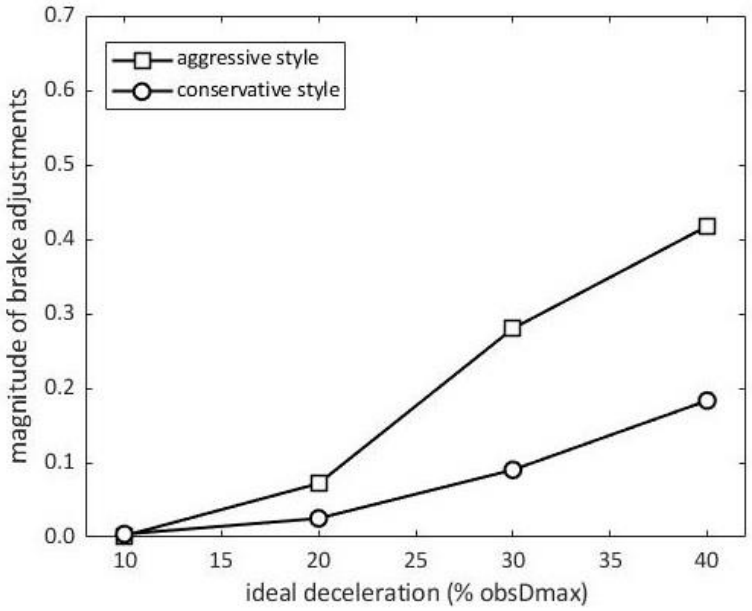


Figure 21: Magnitude of brake adjustments as a function of ideal deceleration (in percentage of observed maximum deceleration) for the two braking styles.

It is noticeable that although closer, even the cyclists using an aggressive style remained relatively distant from their maximum action boundary. That is, irrespective of braking style, participants regulated brake adjustments such that they typically did not exceed an ideal

deceleration of 40% of the observed peak deceleration across the trials of individual participants (Figure 21). In comparison, FAJEN (2005c) reported that, in a car simulator, drivers only started to increase brake adjustments when the ideal deceleration had reached at least ~75% of the maximum deceleration. This discrepancy is perhaps not unexpected as in an in-situ braking there is a real risk of physical damage following a collision compared to braking in a virtual environment. Hence, the cyclists in the current study would have been more cautious (or conservative) than participants in the study by FAJEN (2005c). By taking the maximum deceleration as reference, braking is regulated in relation to critical boundaries (i.e., demarcating possible from impossible action). Yet, traffic users navigating in real-traffic environment may opt to act relative to their preferred rather than critical boundaries instead (i.e., demarcating preferred from non-preferred actions). In this respect, WARREN (1984) demonstrated that individuals using stair climbers could accurately perceive critical boundaries (i.e., relative ratio between the riser height and the leg length), but at the same time preferred riser heights with lower ratios, presumably because at these ratios they expended less energy. Analogously, cyclists in our study may have opted for a preferred action boundary that is lower, more conservative than the critical boundary, as it increases safety. Additionally, VANSTEENKISTE and colleagues (2013) reported that cyclists' gaze strategies differed from the gaze strategies observed in car drivers. In cyclists, gaze depended on cycling speed and lane width, with gaze fixations being more distant at higher speeds. An important question to explore is whether the differences in braking styles that we observed are associated with distinct gaze strategies; if, for example, a more distant gaze invokes a more aggressive braking style (or vice versa).

Strengths and limitations of the study

This study extends Fajen's research on affordance-based control of action from virtual to in-situ environments, where control in action is more challenging and impactful. This is a significant strength, enhancing the validity of affordance-based control to real-world contexts. Except for reproducing Fajen's findings on affordance-based control in (FAJEN, 2005a; 2005c) to cyclists in-situ, the novelty of our work also lies in revealing how different styles of braking emerge.

The manipulation of observed maximum deceleration through bicycle loading did not yield the anticipated results. We determined the observed, or achieved, maximum deceleration by identifying the highest peak of current deceleration that each participant reached in each load condition. This is likely to be an underestimation of the real – or achievable - maximum deceleration. Thus, our methodology assessed the maximum achieved deceleration but did not allow us to ascertain the maximum achievable deceleration. Further investigations should incorporate a separate maximum braking test into the protocol, for instance, by asking participants to stop as fast as possible (while safety must be ensured, of course). Additionally, determining the specific dynamics of the experimental bicycle beforehand, while also considering established braking system standards such as DIN 79010 or ISO 4210-2, would help strengthen the manipulation of braking capabilities in in-situ cycling experiments, without neglecting cyclist safety.

Conclusions

In summary, the results of this study confirm that cyclists avoid collisions by making adaptive brake adjustments that keep ideal deceleration below the maximum achievable deceleration rather than nulling the deviation with ideal deceleration. This is the first study showing the control of braking in an in-situ cycling experiment is affordance-based, that is, braking is controlled by sustaining the perception of stop-ability. While the cyclists adopted the same affordance-based control strategy, they did use different braking styles ranging from aggressive to conservative. The use of the styles was associated with participants cycling experience and are suggested to emerge from differences in calibration between perception and action.

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Chapter 6.

Affordance-based control is scaling to maximum not preferred action boundaries: a study on braking styles of experienced cyclists

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Abstract

This study investigated action scaling in braking relative to preferred and maximum deceleration in cyclists. Additionally, we aimed to corroborate that braking styles emerge from distinct perceptual-motor calibration. Thirty-seven experienced cyclists were asked to cycle uphill and downhill, coming to a stop within the stopping zone. The in-situ experiment effectively manipulated braking capabilities by varying terrain slope, confirming a reduction in both maximum and preferred decelerations in the downhill condition. Participants showed an earlier braking onset with lower ideal deceleration on downhill slope. Interestingly, this slope-related difference disappeared when ideal deceleration was measured in units of maximum deceleration, but not preferred deceleration. Two distinct braking styles were identified: aggressive style, distinguished by the Dcurrent curve exhibiting a skewed parabolic shape, and conservative style, characterised by a consistent linear increase in the Dcurrent curve. The aggressive style was more prevalent specially in the uphill condition. Both braking styles increased the magnitude of brake adjustments as ideal deceleration increased, supporting an affordance-based approach in cycling. Increased ideal deceleration had a greater impact on brake adjustments for the aggressive braking compared to conservative braking. However, the difference between braking styles disappeared when ideal deceleration was scaled to maximum deceleration. This study provides evidence that action scaling of braking in cycling is scaled to maximum rather than preferred boundary. Interestingly, experienced cyclists exhibited consistent calibration between information and action, regardless of braking styles.

Keywords: affordance-based braking, cycling, styles of control, scaling, calibration.

6.1. Introduction

An increasing body of evidence indicates that the successful performance of an action depends on the perception of the affordances of the environment (DICKS et al., 2010; FAJEN, 2005c, 2005a, 2005b, 2007, 2008; GOTARDI et al., 2024; POSTMA et al., 2017, 2018; SEIFERT et al., 2021a; VAN DER KAMP et al., 2018b; ZHENG et al., 2021, 2022). Affordances are action possibilities that emerge from the intrinsic relationship between an organism and its surrounding environment (GIBSON, 1979; STOFFREGEN, 2000; WARREN, 1984). The perception of affordances effectively requires scaling information specifying the organism-environment relationship to action capabilities. Accordingly, in the affordance-based control approach, FAJEN (2007) proposed that action can be successfully controlled by sustaining the perception of the affordance; that is, moving in a manner that ensures that the required action does not exceed the maximum action capabilities of the actor (FAJEN, 2005c, 2005a, 2007, 2008). For instance, FAJEN (2005c) manipulated drivers' action capabilities in a virtual simulator by varying the gain of the braking pedal across groups, resulting in groups with weak (5 m/s^2), medium (7 m/s^2), and strong (9 m/s^2) brake capabilities. The weak capability group showed a lower required or ideal deceleration at braking onset compared to other groups. Interestingly, when ideal deceleration was expressed in units of maximum deceleration, the observed group differences disappeared, suggesting that control was scaled to action capability (FAJEN, 2005c). In a subsequent study, FAJEN (2005a) also demonstrated that brake adjustments became more frequent as the required or ideal deceleration approached the maximum achievable deceleration. In conclusion, drivers scale braking actions to their action capabilities and thus control their action based on perceived affordances (FAJEN, 2005c, 2005a, 2007, 2008).

However, braking behaviour in virtual scenarios may not be fully representative of brake control performed in real world situations. In a simulated environment where the adverse consequences of collisions are minimized, individuals may be inclined to engage in riskier behaviour, i.e., acting closer to (or even going beyond) their maximum capability. To address this gap, we recently conducted an in-situ study to examine whether cyclists employ an affordance-based control strategy to regulate braking, thus potentially allowing different braking control strategies and styles (GOTARDI et al., 2024). Active and inactive cyclists were instructed to stop as close as possible to a stationary obstacle in an indoor gym. Action capabilities were manipulated by loading the bicycle (i.e., no load, load 5kg, and load 10kg). The results revealed that cyclists increased the magnitude of brake adjustments as the required or ideal deceleration approached the action boundary, regardless of the bike load. This corroborated previous findings (e.g., FAJEN, 2005a) and indicates that cyclists indeed adopt an affordance-based control strategy for braking. However, the additional loads were probably too light to affect control. Furthermore, we also observed that the participants used two braking styles: a more aggressive style (i.e., late braking onset and a sharp increase in ideal deceleration) and a conservative style (i.e., early braking onset and gradual increase in ideal deceleration). The more aggressive style was prevalent among active cyclists, while inactive cyclists were more often conservative. And although both styles showed a proportional increase in the magnitude of brake adjustments, this increase was greater in the aggressive style. GOTARDI et al. (2024) proposed that this reflects a difference in calibration, the ideal

deceleration having a stronger impact on the brake adjustments for the aggressive style than for the conservative style.

In the current study, we addressed two additional questions raised by GOTARDI et al. (2024) and FAJEN's earlier work (FAJEN, 2005a; 2005c). First, studies on affordance-based control of braking and other actions assume that information is scaled to the maximum action capability (DIAZ et al., 2018; FAJEN, 2005c, 2005a, 2008; GOTARDI et al., 2024; ZHENG et al., 2022). However, perhaps depending on the severity of the consequences of unsuccessful performance, the information could also be scaled to one's preferred capabilities. In braking, the maximum achievable deceleration marks the boundary that separates possible from impossible actions. Going beyond this boundary would imply a collision, potentially with physical consequences. Alternatively, drivers or cyclists may choose to act relative to their preferred deceleration, which demarcates preferred from nonpreferred actions. This preferred boundary would typically be lower than the maximum boundary and would present less risky navigation. WARREN (1984) showed that individuals climbing stairs accurately perceived both the critical or maximum riser height and the optimal or preferred riser height relative to their leg length. Participants exhibited a preference for lower than maximum riser heights, presumably because it was associated with a reduction in energy expenditure (WARREN, 1984). Analogously, we found in our previous study (GOTARDI et al., 2024) that cyclists opted to act relatively distantly from their maximum boundary. They consistently adjusted their brakes to maintain the ideal deceleration at approximately 40% of the maximum achieved deceleration. By contrast, FAJEN (2005c) reported that drivers in a simulated environment adjusted the brake only when the ideal deceleration approached approximately 75% of the maximum deceleration.

Therefore, the first objective of the current study was to examine whether action scaling in braking is toward the maximum or preferred deceleration. To this end, we manipulated the momentary action capabilities of experienced cyclists by asking them to perform a spatially controlled stop on downhill and uphill surfaces. The downhill slope results in a lower maximum deceleration than the uphill slope. The factual maximum and preferred decelerations were assessed in two separate braking tests for both slopes. The maximum braking test required participants to stop as fast as possible, while the preferred braking test asked participants to stop as they would do in their daily cycling routine. Next, in the experimental trials, participants were instructed to stop the bike in a designated area when cycling downhill and uphill. We hypothesized that cyclists show an earlier brake onset – at a lower ideal deceleration – in the downhill condition compared to the uphill condition. However, these differences in ideal deceleration were expected to dissolve if they were scaled to or expressed in units of maximum achievable deceleration (i.e., %Dmax) and/or if scaled to preferred deceleration (%Dpref). The latter would guide cyclists to reduce the risks of unsuccessful performance by choosing to act within the preferred action rather than the maximum action boundary. Second, it is pertinent to investigate how different action styles should be understood within an affordance-based control approach. In our recent in situ braking study (GOTARDI et al., 2024), we proposed that braking styles emerged from differences in calibration between information and action. That is, our exploratory analyses suggested that changes in ideal deceleration had a stronger impact on the magnitude of brake adjustments for the more aggressive style of braking than for the

conservative style. In these analyses, the ideal deceleration was scaled to the maximum achieved deceleration.

The present study investigates this issue further and aims to corroborate that different styles reflect different calibration. We expected experienced cyclists to adopt a more aggressive style of braking in the uphill condition than in the downhill condition, since downhill the maximum achievable deceleration will be lower. Importantly, we also anticipated that for both braking styles, the magnitude of the brake adjustment increases as required or ideal deceleration increases, and we expected that the increase is stronger (i.e., as reflected by a steeper slope in the relationship between ideal deceleration and magnitude of brake adjustment) for the more aggressive style. Corroborating our previous finding (GOTARDI et al., 2024), we expected that this would also hold when scaling to either the maximum achievable deceleration (i.e., % Dmax) or the preferred deceleration (% Dpref). That is, regardless of whether cyclists scale their actions relative to their maximum or preferred capabilities, differences in braking styles become evident through distinct calibration.

6.2. Method

Participants

An a priori power analysis (G*Power 3.1.9.7) for a repeated measures analysis of variance (RM-ANOVA) indicated a minimum sample size of 34 participants (i.e., $\beta = .80$, $\alpha = .05$, effect size $f = .25$). Thirty-seven adults (29 females, between 18 and 50 years of age) voluntarily participated in this study and reported regular use of the bicycle as a way of commuting through the city, at least three times a week, with weekly and annually distances pedalled of at least 20 and 500 km, respectively (Gotardi et al., 2024; Lehtonen et al., 2016). Participants were recruited by email among students and staff of the Vrije Universiteit Amsterdam. All participants had normal or corrected to normal vision and no sensorimotor or neurological impairments. The protocol was approved by the Scientific and Ethical Review Board of the Faculty of Behavioural and Movement Sciences of the Vrije Universiteit Amsterdam (VCWE-2020-151R1) and was carried out according to the principles of the Declaration of Helsinki. Participants signed informed consent prior to the start of the experiment.

Environment and apparatus

The study was carried out on a public ramp in the city of Amsterdam. The ramp is located on the top deck of a tunnel, surrounded by schools and buildings, and is mainly used to park bicycles. There is no through traffic. Therefore, it offered a safe place for participants to perform the experimental task without interference from vehicles, other bicycles, and pedestrians. The experimental bicycle was a typical Dutch bicycle (Avalon omafiets Export, 28 inch) with a coaster brake (Figure 22a). Coaster brakes (or back-pedal brakes) are located in the rear wheel hub of the bicycle; braking is applied by rotating the pedals in reverse. A speedometer (SIGMA Sport BC 5.0) attached to the bicycle informed participants about their current speed. On the ramp (slope of 2.6°), a 30 m long cycle path was demarcated with a midline at 15 m. At the edges of the cycle path, two rectangle stopping zones measuring 180 x 90 cm (length x width) were drawn on the floor, which was the same length as the bicycle

(Figure 22b). Two digital cameras (Fujifilm FinePix XP120) recorded the bicycle trajectory in a frontal-parallel view in relation to the cycle path at a sampling rate of 59.94 Hz and resolution of 1920x1080.



Figure 22: a) The experimental bicycle with a coaster brake by which braking is activated by rotating the pedals in reverse. The headlight was wrapped in aluminium foil for motion tracking purposes; b) The first author riding the experimental bicycle towards the stopping area downhill; c) Computer-generated image representing the cycle path, starting points, midline, and stopping areas for both slope conditions

Procedure

Data collection was carried out during the COVID-19 pandemic, which demanded strict adherence to the Dutch government guidelines. Therefore, the experiment was carried out outdoors, with social distancing and regular disinfection of the experimental bicycle with 70% alcohol at the conclusion of each participant's session, thus ensuring a safe research environment. In the initial five minutes, participants were tasked with familiarizing themselves with the bicycle, the designated cycle path, and the braking task in both the downhill and the uphill directions. Individual adjustments were made to the bicycle saddle height, ensuring that

participants could comfortably touch the ground with their toes while seated. Subsequently, braking tests and an experimental block were performed.

Braking capabilities tests

Pretest. The experiment started with participants performing a maximum braking test (i.e., BMAX) and a preferred braking test (i.e., BPREF). In both tests, participants were asked to approach the midline at a speed between 14 and 16 km/h in both the downhill and uphill slope conditions. Upon crossing the midline, they were instructed to stop as fast as possible (for the BMAX test) or to stop as they normally did in their daily cycling routine (for the BPREF test). The BMAX test demanded that participants apply maximum braking force, evaluating their maximum action capabilities. The BPREF test aimed to assess the preferred braking force of the participants. Both tests were performed three times downhill and three times uphill. The sequence of the slope trials was alternated for all participants. For instance, when a participant started the BMAX test or the BPREF test with a trial in the uphill slope condition, the subsequent condition was the downhill slope, and so on until the conclusion of the braking tests. Participants performed the BMAX test and immediately after the BPREF test. *Post-test.* Following the experimental block, the BMAX post-test was conducted for the second time to check the potential effects of physical fatigue and/or practice.

Experimental block

Participants were asked to cycle uphill and downhill, coming to a stop within the stopping zone (i.e., a rectangle marked on the floor, Figure 22c). The length of the rectangle matched the length of the bicycle, which required an accurate braking from the participants to ensure that the bicycle fit perfectly within the rectangle the moment it came to a complete stop (i.e., the velocity reached zero). Participants were instructed to keep the bicycle in the same position after stopping (with the feet on the ground) until the experimenter had measured the distance between the frontal edge of the front wheel and the frontal edge of the rectangle. Positive values represent that the bicycle's front wheel stopped in front of the leading edge of the rectangle, while negative values were assigned to stops where the front bicycle wheel stopped behind the leading edge of the rectangle. Two starting points were placed on the experimental ramp, one at the bottom and another at the top of the slope for downhill and uphill conditions, respectively (Figure 22c). The participants were instructed to start pedalling from the respective starting points, aiming to attain a speed of 14-16 km/h as indicated by the speedometer attached to the steer, before reaching the midline after approximately 15 m. After crossing the midline with the bicycle's front wheel, participants were allowed to start braking, aiming to stop exactly within the stopping zone. Ten trials were performed in each slope condition, totalling 20 trials. The slope trials in the experimental block followed the same alternating sequence as the braking tests. The start condition was counterbalanced among participants.

Data analysis

The trajectory of the headlight of the bicycle was tracked frame-by-frame using Kinovea software (version 0.9.1). The horizontal and vertical coordinates of the trajectory were passed

through a low-pass filter (2nd order Butterworth) to remove noise (Winter, 2009). The total horizontal displacement of the bicycle was calculated for each participant and exported as tabular data in CSV format for further processing with MATLAB software (The MathWorks Inc., USA, version R2018b). The analyses of the control of deceleration and adjustments in braking were based on Fajen's studies (2005a; 2005c; see also Gotardi et al., 2024). From the horizontal displacement, we calculated the velocity, the deceleration (i.e., Dcurrent) and the required or ideal deceleration (Dideal). Dideal refers to the constant rate of deceleration required to exactly stop the bicycle in the stopping zone without making any further adjustments (Fajen, 2007). The Dcurrent and Dideal vectors were resampled in 200-ms intervals, which included only the intervals in which the deceleration error was nulled. For each 200-ms interval, brake adjustments were determined by examining the difference between the final Dcurrent value and the initial value exceeded 0.03 m/s² (Fajen, 2005a). The magnitude of brake adjustments was determined as the square root of the sum of the squares of consecutive adjustments ($\sqrt{b_1^2 + b_2^2}$). A magnitude value was calculated for each pair of brake adjustments (e.g., b_1 and b_2; b_2 and b_3; and so on). This magnitude represents the distance between two adjustments, with higher values indicating stronger adjustments. From the examination of the linear parameters (velocity, Dcurrent, and Dideal) and brake adjustment analysis, the following dependent variables were calculated:

Braking capabilities: Participants' performance in the braking tests was assessed by identifying the peak value of Dcurrent in each trial, denoted as maximum deceleration (Dmax) for the BMAX test and preferred deceleration (Dpref) for the BPREF test. In the BMAX test, performance was determined by selecting the highest Dmax among the three trials, while in the BPREF test, it was evaluated through the average of the three Dpref values. Six participants showed higher Dpref than Dmax on the downhill slope. In these cases, the values of Dpref and Dmax were equated.

Performance outcome: the velocity at the moment of crossing the midline (i.e., velocity at midline) was computed to confirm that participants kept the bicycle approaching speed within the specified range of 14-16 km/h. For braking accuracy, the final stopping distance was determined by measuring the distance (m) between the leading edge of the front wheel and the leading edge of the stopping zone in the last frame, which corresponds to when the bicycle's velocity reached zero. The mean and standard deviation of the final stopping distance were calculated. The analysis of braking onset was conducted separately for each slope condition. In doing so, we aimed to distinguish increases in deceleration resulting from brake adjustments (i.e., active braking) from those arising from stopping pedalling (i.e., passive braking). This is not possible from fluctuations in deceleration. Therefore, in the downhill condition, where any increase in deceleration (i.e., > 0.03 m/s^2) implies an active brake adjustment, the braking onset (s) was defined as the moment of the first brake adjustment. In contrast, uphill trials presented an additional challenge, as increases in deceleration could stem from both active braking and from stopping the pedalling (i.e., passive braking). To address this, we established the first active brake adjustment through a two-step verification process: first, we identified increases in deceleration (i.e., > 0.03 m/s^2), and second, we reviewed the videos to confirm whether or not the increase represented active braking through observable leg movements. The first active brake was used for braking onset.

Action scaling: To further explore the perception-action coupling at brake onset (i.e., controlling the first brake adjustment), we identified Dideal at brake onset (measured in m/s^2). To examine whether control was based on affordances, we investigated whether variations in Dideal at brake onset across different slopes disappeared when scaled to action (Fajen, 2005c; 2007). In this regard, we conducted an analysis of scaling relative to both the maximum achievable deceleration, Dideal at brake onset (% Dmax), and the preferred deceleration, Dideal at brake onset (% Dpref). Next, Dideal at brake onset as percentages of both Dmax and Dpref were submitted to a dispersion analysis. In doing so, we aimed to identify whether, at brake onset, the percentage of Dmax or the percentage of Dpref was most consistent. Index of dispersion (IOD = $\sigma 2/\mu$) was calculated for each participant across the two slope conditions. The lowest IOD (i.e., either for Dmax or Dpref) was taken to indicate the action capability to which information is scaled, that is, that acts to constrain the action boundary.

Styles of braking: To identify different styles of braking, the Dcurrent time series on each trial were normalized using a z-score transformation. Then, a similarity index was obtained for each pair of trials with dynamic time warping (DTW). DTW allowed us to compare time series with different lengths by creating a distance matrix containing the distance between each point of the two-time series (e.g., trial-1 vs. trial-2) (Cleasby et al., 2019). The similarity index value was then used to categorize the trials into clusters with a Partition Around Medoids (PAM) method. The DTW and clustering analysis was run in RStudio (Version: 2023.12.1+402). The frequency distribution of different clusters for the downhill and uphill conditions was assessed. Each cluster was taken to represent a different style of braking. To examine whether different styles of braking reflect differences in calibration, we determined the (linear) relationship between the magnitude of brake adjustment and Dideal. Each brake adjustment occurs at a specific value of Dideal. The brake adjustments were grouped into four equally spaced bins (or intervals) of Dideal (m/s^2). The bins ranged from zero to the maximum Dideal. The magnitude of brake adjustment for each Dideal bin was calculated, and the strength of the relationship between Dideal and the magnitude of the brake adjustment (i.e., the slope of the regression line) was determined. Note that the initial brake adjustment was excluded from this analysis. Finally, this analysis was also performed for Dideal expressed in % Dmax or in % Dpref, depending on the measure that constrains the action boundary. That is, if cyclists scaled their action relative to the maximum deceleration, the relationship between Dideal (% Dmax) and magnitude of adjustments was assessed. Otherwise, Dideal (% Dpref) was adopted as the dependent variable in the regression analysis.

Statistical analysis

Shapiro Wilk normality tests were performed on all dependent variables. For the normally distributed variables, we conducted independent samples t-tests (downhill vs. uphill). In case the assumption of normal distribution was violated, the nonparametric equivalent Wilcoxon test was conducted. *Braking capabilities:* To assess the impact of slope in the braking pre-tests, a Wilcoxon test (downhill vs. uphill) was conducted for the BMAX, while the BPREF utilized a t-test for the same comparison. For the BMAX post-test, also a Wilcoxon test was conducted to assess differences between downhill and uphill. Next, to explore the potential effects of physical fatigue or practice, we performed separate t-tests (BMAX pre-test vs. BMAX post-test) for both downhill and uphill slope conditions. *Performance outcome:* To

check whether participants maintained the instructed speed (14-16 km/h) across slope conditions, velocity at midline was submitted to a t-test. Braking accuracy was assessed through Wilcoxon tests, while the mean and standard deviation of the final stopping distance and brake onset were analysed with t-tests. *Action scaling:* We compare Dideal at brake onset (m/s^2) in downhill and uphill conditions using a Wilcoxon test. To evaluate action scaling, we conducted a Wilcoxon test for Dideal at brake onset (% Dmax) while the Dideal at brake onset (% Dpref) was submitted to a t-test. Furthermore, we conducted a t-test to compare the indices of dispersion (for percentages of Dmax vs. Dpref). *Styles of braking:* A chi-square test examined whether the distribution of clusters differed between slope conditions. As Dideal increases, participants are expected to adjust the magnitude of braking accordingly (Fajen, 2005a; Gotardi et al., 2024). To investigate this relation, we conducted a linear regression analysis, examining the magnitude of adjustments as a function of Dideal for each identified cluster. Separate analyses were run per participant. To validate our hypothesis that different styles of braking (as represented by different clusters) reflect calibration, we assessed the difference in the distance between the regression lines of the clusters. Furthermore, the regression analysis was employed by using Dideal (% Dmax) or Dideal (% Dpref) as the dependent variable, depending on the measure that constrains the action boundary (Dmax or Dpref). Distinct analyses were conducted for Dideal (m/s^2), and Dideal (% Dmax) or Dideal (% Dpref). All statistical analyses were performed with SPSS Statistics (17.0.1). Tukey Honestly Significant Difference tests and Greenhouse-Geisser degrees of freedom adjustments were applied as needed. The significance level (alpha) was set at 0.05. For the t-tests, the effect sizes were calculated using Cohen's d, with values of 0.2, 0.5, and 0.8 representing small, medium, and large effect sizes, respectively (Cohen, 1988). For the Wilcoxon tests, the effect sizes (*r*) were calculated by dividing the Z-score by the square root of N (total number of pairs), with 0 indicating no effect and values closer to -1 or 1 indicating a stronger effect (Fritz et al., 2012).

6.3. Results

Braking capabilities

Figure 23 shows the effect of slope on the maximum and preferred decelerations during braking tests. The maximum deceleration observed in the BMAX pre-test was significantly higher in the uphill condition compared to the downhill condition ($W = 97$, $p < .001$, $r = -0.233$). Similarly, the BMAX post-test revealed a significantly higher maximum deceleration in the uphill condition compared to the downhill condition ($W = 85.5$, $p < .001$, $r = -0.128$). In the BPREF test, the preferred deceleration was found to be significantly higher in the uphill condition compared to the downhill condition ($t(36) = -3.095$, $p = .002$, $d = -0.719$). No significant difference was observed between the BMAX pre-test and BMAX post-test in both slope conditions.

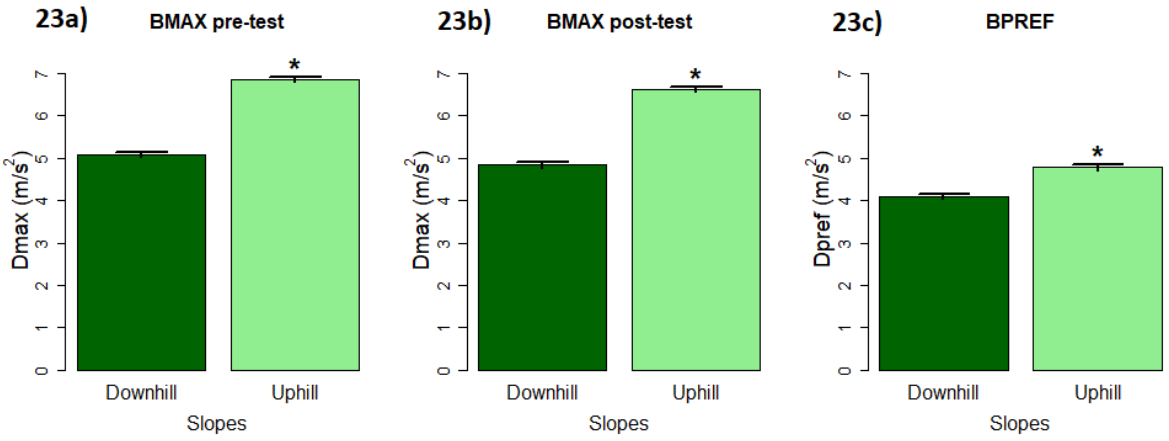


Figure 23: a) maximum deceleration (Dmax) in the maximum braking (BMAX) pre-test and b) post-test, and c) preferred deceleration (Dpref) in the preferred braking (BPREF) test in downhill (dark green) and uphill (light green) slope conditions.

Performance outcome

The velocity at midline (Figure 24a) revealed that the speeds at which participants crossed the midline did not differ between slope conditions, confirming their adherence to task instructions. For braking accuracy, the mean (Figure 24b) and standard deviation (Figure 24c) of final stopping distance showed no significant differences across slope conditions. However, brake onset showed that the participants started to brake earlier (Figure 24d) in the downhill condition compared to the uphill condition ($t(36) = -11.545$, $p < .001$, $d = -2.684$).

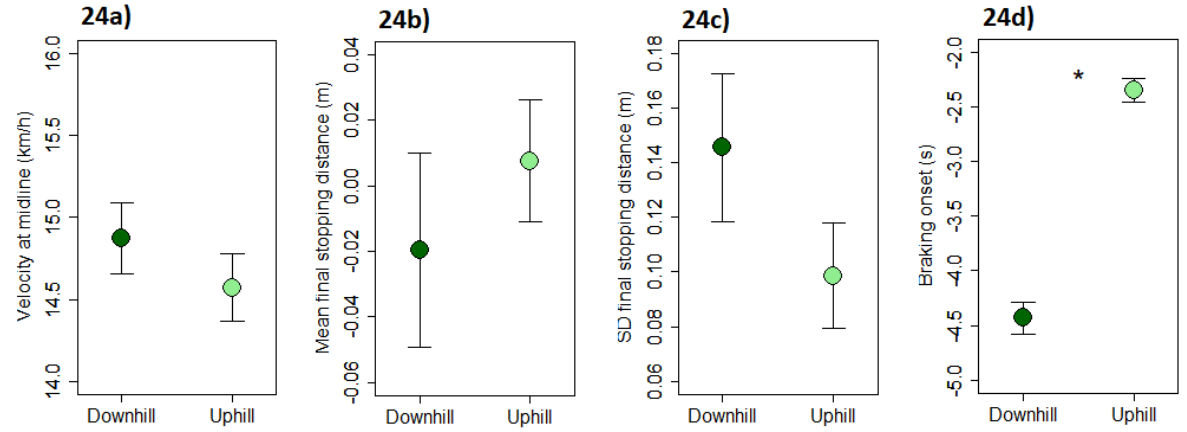


Figure 24: a) velocity at midline, b) average final stopping distance, c) average within-subject standard deviation (SD) final stopping distance, and d) braking onset in downhill (dark green) and uphill (light green) slope conditions.

Action scaling

The analyses for brake onset revealed significantly higher values of Dideal in the uphill condition compared to the downhill condition (W = 355.5, p < .001, *r* = 0.704) (Figure 25a). However, this slope-related difference disappeared when Dideal at brake onset was expressed in units of Dmax (Figure 25b). Interestingly, when Dideal at brake onset was expressed as percentage of Dpref (Figure 25c), a significant difference for slope remained (t(36) = -2.649, p = .012, d = -0.451). For the dispersion analysis (Figure 25d), a significantly lower index of dispersion for Dideal at brake onset as a percentage of Dmax was found in comparison to Dideal at braking onset as a percentage of Dpref (t(36) = -9.002, p < .001, d = -0.598).

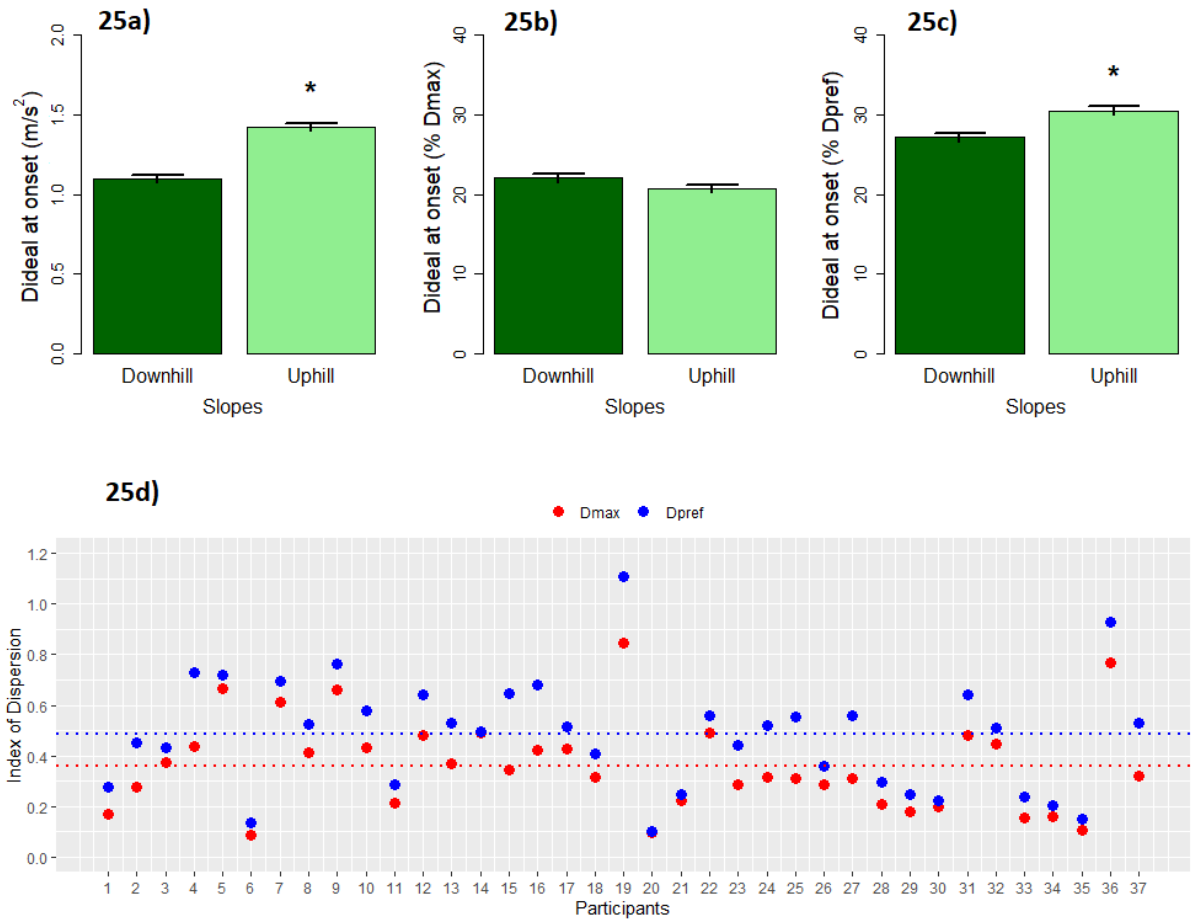


Figure 25: a) Dideal at brake onset expressed in meters per second squared, b) Dideal at brake onset expressed as percentage of maximum deceleration, and c) Dideal at brake onset expressed as percentage of preferred deceleration in downhill (dark green) and uphill (light green) slope conditions, d) index of dispersion across all trials (downhill and uphill) for Dideal at brake onset as a percentage of maximum deceleration (red) and Dideal at brake onset as a percentage of preferred deceleration (blue) for each participant (x-axis).

Styles of braking

Two clusters emerged from the analysis, characterizing two distinct braking styles: i) cluster 1 (i.e., conservative style), characterized by a linear growth in the Dcurrent curve

throughout the trial; and ii) cluster 2 (i.e., a more aggressive style), the Dcurrent curve shows a skewed parabolic shape (Figure 26a). The frequency distributions of clusters 1 and 2 between groups are reported in Table 7. Chi-square analysis showed a significant association between the style of braking and slope, indicating that cluster 2 was more prevalent especially in the uphill condition, χ^2 (1) = 41.44, p < .001.

The results of the linear regression indicated that Dideal (m/s^2) significantly predicted the magnitude of the brake adjustments in both cluster 1 (β = .136, p = .003, 95% CI [.114, .158]) and cluster 2 (β = .316, p = .020, 95% CI [.095, .538]). Similarly, a significant relationship was found between magnitude of adjustments and Dideal (% Dmax) was found both for cluster 1 (β = .008, p < .001, 95% CI [.007, .010]) and for cluster 2 (β = .007, p = .022, 95% CI [.002, .012]). Our hypothesis that cyclists would increase the magnitude of brake adjustments as Dideal increased was confirmed in all analyses, regardless of cluster (Figure 26b). As confirmed by Welch's Two Sample t-test, the distance between the Clusters' regression lines when Dideal (m/s^2) is significantly larger compared to the distance between the Clusters' regression lines when Dideal (%Dmax), (mean difference = 0.052, 95% CI [0.050, 0.055], t(169.41) = 36.771, p < .001).

Table 7. Contingency table for the frequency distribution of clusters by slope conditions.

	Downhill	Uphill	Total
Cluster 1	166	124	290
Cluster 2	204	246	450
Total	370	370	740

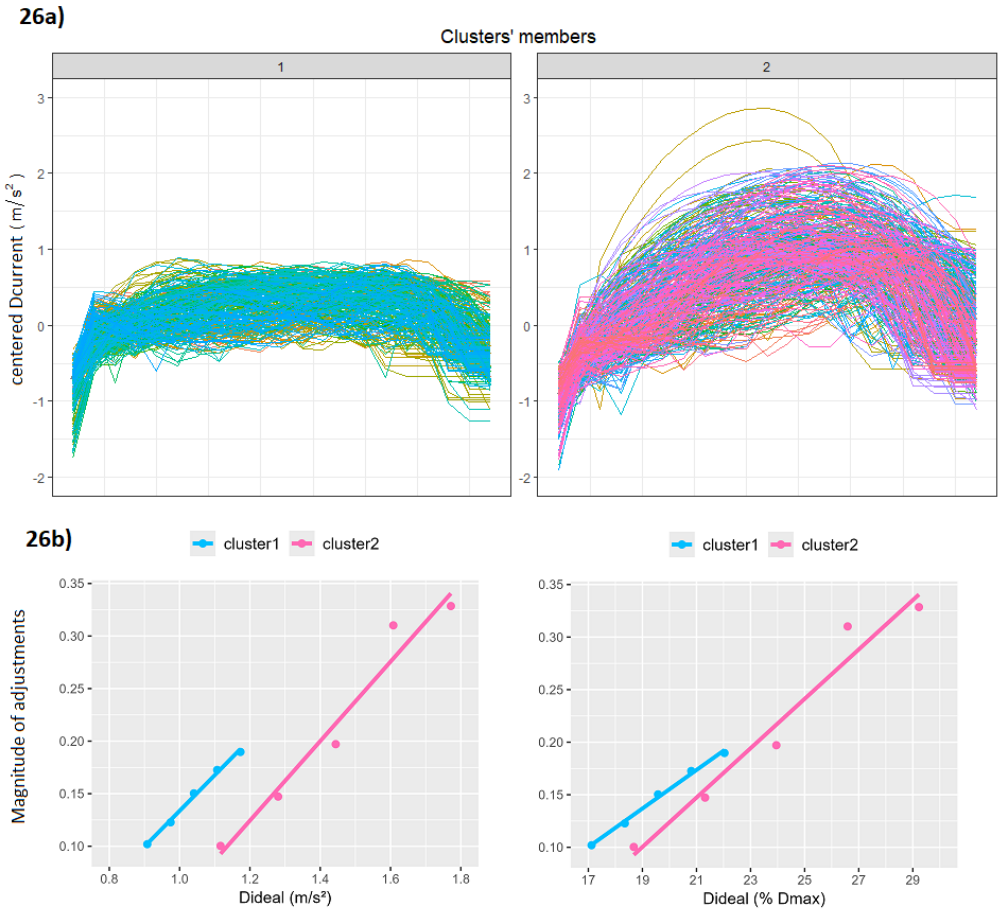


Figure 26: a) Styles of braking control emerged from the clustering analysis: i) cluster 1 (conservative style), Dcurrent curve grows linearly flat and low peak; ii) cluster 2 (aggressive style), Dcurrent curve shows a skewed parabolic shape, with a high and steep peak; b) Magnitude of brake adjustments as a function of Dideal (m/s^2) and Dideal (% Dmax) for the two clusters.

6.4. Discussion

This study investigated whether action scaling in braking is relative to preferred deceleration or maximum achievable deceleration. Additionally, we aimed to corroborate that braking styles emerge from distinct calibration between information and action (GOTARDI et al., 2024). Participants were instructed to ride a conventional Dutch bicycle on an outdoor ramp at 14-16km/h, aiming to come to a stop within a designated stopping zone in downhill and uphill conditions. Analysis of velocity at the midline revealed no slope-related effect, confirming participants' adherence to the task instructions. No differences in braking performance, especially mean and SD final stopping distance, were found between the downhill and uphill slopes. That is, participants were accurate in both conditions, underlining their cycling skills. The participants' braking capabilities were dependent on the slope condition, with the downhill condition resulting in a reduced maximum achievable deceleration compared to the uphill condition. Our primary hypothesis posited that braking on downhill slope requires an earlier onset at lower values of ideal deceleration, due to the reduction in maximum achievable deceleration. However, it was anticipated that this slope-related

difference in braking control disappears when ideal deceleration is considered relative to either the maximum (%Dmax) or preferred (%Dpref) deceleration. Our results validate this hypothesis, revealing that braking is scaled towards the maximum action boundary, and not the preferred boundary. In terms of braking styles, we aimed to confirm our suggestion that the observed conservative and more aggressive braking styles reflect distinct information-action calibration. By contrast, we found that the two braking styles exhibited similar calibration when ideal deceleration was relative to maximum achievable deceleration. Below we discuss these hypotheses in more detail.

Braking capabilities

Participants' braking capabilities were dependent on the slope condition, in align with our expectations. In the maximum braking test, participants exhibited lower deceleration in the downhill than uphill condition. Similarly, the preferred braking test revealed lower preferred deceleration in downhill than uphill condition. This confirms the effectiveness of our protocol in altering cyclists' braking capabilities by varying the terrain slope. We also expected that all participants would demonstrate a greater maximum deceleration compared to their preferred deceleration in both slope conditions. However, during the braking tests on a downhill slope, six participants exhibited a higher preferred deceleration than the maximum deceleration. It's worth noting that all participants realized the maximum test before the preferred test, and this sequence might have impacted the results for these specific participants. Nevertheless, when considering the overall group average, the performance of these few participants did not alter the significant difference between the braking tests. To address this for the analysis of scaling and calibration, we equalized both maximum and preferred decelerations for those participants. Finally, consistent pre- and post-test maximum deceleration in both slope conditions indicates that participants remained unaffected by potential physical fatigue and/or practice during the experiment.

Action scaling

We sought to understand whether action scaling in braking would be relative to the cyclists' maximum or preferred deceleration. Confirming our hypothesis, the analyses revealed an earlier braking onset, with lower values of Dideal, in the downhill condition compared to the uphill condition. However, this slope-related difference disappeared when Dideal at braking onset was scaled to maximum deceleration (%Dmax), but not to preferred deceleration (%Dpref). Furthermore, participants consistently demonstrated a lower index of dispersion for Dideal at braking onset in percentage of Dmax than in percentage of Dpref. These findings emphasize that the experienced cyclists in this study scaled brake adjustments towards their maximum boundary, but not preferred boundary, to compensate for the reduced maximum deceleration in the downhill condition. This result corroborates the hypothesis that information is scaled to the maximum action boundary, providing strong evidence supporting affordance-based control (FAJEN, 2005a; 2005c; 2008; DIAZ et al., 2015; ZHENG et al., 2022). In our previous study (GOTARDI et al., 2024), we assessed the maximum *achieved* deceleration, determined by the highest peak of current deceleration. This measurement only captures the current maximum deceleration but fails to account for the maximum *achievable* deceleration. Our current protocol, using the maximum braking test, addresses this limitation and allowed

us to investigate action scaling in braking towards the maximum deceleration. The maximum action boundary serves as the threshold distinguishing possible from impossible actions (FAJEN, 2007). On the other hand, the preferred action boundary should demarcate preferred from non-preferred actions. That is, to detect the possible and most economical action, referred to as best-fit affordances (WARREN 1984). Therefore, by scaling brake adjustments to the maximum boundary, the experienced cyclists in this study sought information about whether braking was afforded or not (and consequently the risk of collisions), rather than whether the preferred braking (economical action) was afforded or not. The predominance of the maximum boundary on the cyclists' brake adjustments could be attributed to a collision avoidance bias. In in-situ braking, such as the current study, there is a real risk of physical damage following a collision compared to braking in a virtual environment. Then to minimize the risk of collisions, it is crucial to maintain a significant distance between the ideal deceleration and the maximum deceleration. The present study shows that participants performed brake adjustments when the ideal deceleration was at approximately 20-25% of their maximum deceleration. Analogously, in our previous in-situ braking study (GOTARDI et al., 2024), cyclists were observed to execute brake adjustments when the ideal deceleration ranged from 10% to 40% of the maximum achieved deceleration. In contrast, in all Fajen's virtual braking experiments (2005a; 2005c), revealed that drivers maintained Dideal within the range of 50-90% of maximum deceleration. This illustrates that in in-situ braking experiments, cyclists seem to act within their maximum rather than their preferred capacity, even if it means staying relatively distant from the maximum boundary.

Braking styles

In addition, we sought to further understand how diverse styles of braking emerge in the context of changing action capabilities. We previously hypothesized that participants would adopt a more aggressive style of braking in the uphill condition than in the downhill condition, due to the reduced maximum deceleration in the latter. The clustering analysis confirmed the existence of two distinct braking styles. The conservative style (cluster 1), characterized by a consistent linear increase in the Dcurrent curve throughout the trial. Otherwise, a more aggressive style (cluster 2), distinguished by the Dcurrent curve exhibiting a skewed parabolic shape. While our earlier study (GOTARDI et al., 2024) also recognized similar braking styles, the identification was previously based on visual inspections. That is, two raters examined the plots depicting Dideal and Dcurrent curves for each trial. We then classified braking styles by assessing the similarities between the curves. In contrast, the present study incorporates data driven techniques such as Dynamic Time Warping (DTW) and clustering analyses. This methodological improvement allows for a more systematic and objective categorization of braking styles, providing a more robust description of the participant's behaviour. By leveraging these tools, we have elevated the precision and reliability of our research on styles of braking. The aggressive braking style was more prevalent especially in the uphill compared to the downhill condition, validating our initial hypothesis. In the downhill condition, the reduced maximum deceleration seems to have influenced participants to adopt a more conservative braking style. Importantly, both braking styles increased the magnitude of brake adjustments as ideal deceleration increased (i.e., closer to the maximum action boundary), supporting that braking in cycling is affordance-based (GOTARDI et al., 2024; FAJEN, 2005a;

2005c; 2007). Corroborating our previous finding (GOTARDI et al., 2024), we expected a steeper slope of the regression line between ideal deceleration (% Dmax) and magnitude of brake adjustments for the aggressive style compared to the conservative style. This result would indicate that different braking styles emerge from distinct calibration between information and action. As anticipated, our findings revealed a more pronounced impact of ideal deceleration (measured in m/s^2) on brake adjustments for the aggressive than the conservative braking. Additionally, the distance between the regression lines of the clusters (i.e., braking styles) disappeared when ideal deceleration was measured in units of maximum deceleration (%Dmax). In other words, different braking styles exhibited similar calibration. Previously we found distinct calibration between aggressive and conservative braking styles (GOTARDI et al., 2024). The divergence in results between the two studies may be attributed to the measurement of maximum deceleration (as cited above).

Another potential factor influencing the braking styles of cyclists could be their level of experience. Existing studies suggest that experienced individuals have greater maximum action capabilities and more adaptive perceptual-motor calibration (DICKS et al., 2010; HACQUES et al., 2021; HIGUCHI et al., 2011; SEIFERT et al., 2021a, 2021b; ZHENG et al., 2022). In our preceding investigation (GOTARDI et al., 2024), although we found that experienced cyclists were more likely to exhibit the aggressive style of braking, both aggressive and conservative styles were evident among both experienced and inexperienced cyclists. Thus, the observed difference in calibration between braking styles may have been the result of a different calibration among the inexperienced cyclists. The present study, on the other hand, only focused on cyclists with extensive daily city biking experience, eliminating the experience/styles confounding. This study appears to be the first to find evidence of calibration between information and action for different styles of braking in cycling. More research should explore how experience and calibration interplay in the adoption of different braking styles. Additionally, future studies should consider the potential effects of different personalities (e.g., anxious vs. non-anxious) on the adoption of braking styles and calibration.

Conclusions

In summary, this study found that cyclists adapt braking based on terrain slope. Our findings confirm that experienced cyclists scaled brake adjustments to their maximum action rather than preferred action boundary. Two braking styles, conservative and aggressive, were identified, with the aggressive style more prevalent in the uphill slope condition. Increasing ideal deceleration had a stronger impact on the magnitude of brake adjustments for the aggressive braking style. However, consistent calibration between information and action was maintained across braking styles. The study contributes insights into how cyclists regulate braking, supporting the affordance-based approach.

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Chapter 7.

General Discussion

This thesis addresses how visual information guides drivers' and cyclists' actions in traffic navigation by comparing distinct theoretical frameworks. The model-based approach (LOOMIS; BEALL, 2004) posits that visual information is processed cognitively, separating perception and action into two distinct stages. In this view, drivers and cyclists first perceive their surroundings and create mental representations, which then guide actions such as braking or steering. Research presented in Chapters 2, 3, and 4 examines gaze behaviour and its role in attentional control. The findings indicate that factors such as anxiety, aging, and Parkinson's disease negatively impact driving performance by leading to more restricted and less adaptive gaze patterns. These results suggest that cognitive processes play a crucial role in allocating attentional resources to manage visual information, thereby compensating for the challenges faced in maintaining driving or cycling performance. In contrast, the affordance-based approach (FAJEN, 2007), rooted in GIBSON's ecological theory (1979), suggests that drivers and cyclists directly perceive affordances - action possibilities - in their environment without the need for cognitive mediation. According to this perspective, visual information is not processed or transformed into internal models; rather, individuals use real-time visual cues like optic flow to guide their actions. The findings in Chapters 5 and 6 support this view, showing that cyclists adopt an affordance-based braking strategy. They continuously adjust their deceleration to prevent collisions by keeping it within their capabilities.

By examining two contrasting theoretical frameworks—the model-based and affordance-based approaches—this thesis offers a comprehensive analysis of how visual information guides action in traffic navigation. Our findings highlight both the cognitive processes underlying gaze behaviour and attentional control, as well as the affordance-based actions used by drivers and cyclists. The comparison of these frameworks suggests that the affordance-based approach provides a more parsimonious and representative explanation for understanding visually guided actions in real-world urban traffic environments.

In this General discussion, I start by examining the different measures used to understand the visual guidance of actions in road traffic. Gaze behaviour as a guide of discovery for exploring perception-action coupling is reviewed and discussed. The second part focuses on the implications of adopting an affordance-based theoretical approach to investigating visually guided navigation. Finally, we explore the strengths and limitations of the present series of studies, suggesting directions for future investigations.

7.1. Measuring the perception-action coupling

Initially, my guide to discovery involved measuring drivers' gaze behaviour during virtual navigation, was rooted in cognitivist approaches (FODOR; PYLYSHYN, 1981; LOOMIS et al., 1992; LOOMIS; BEALL, 2004; MARR, 1982; PHILBECK et al., 1997). Chapter 2 explored the impact of induced state anxiety on both experienced and inexperienced drivers by recording their gaze behaviour and driving performance in a driving simulator. The results indicated that in the high-anxiety condition, drivers exhibited a greater number of fixations towards threatening stimuli (i.e., other cars on the road), particularly the inexperienced drivers did so, corroborating previous findings in sport contexts (MURRAY; JANELLE, 2003b; NAVARRO et al., 2013; NIEUWENHUYS et al., 2008). This attentional shifting was accompanied by poorer performance (e.g., less time spent driving under the speed

limit and a greater occurrence of collisions) under high-anxiety condition. Moreover, Chapter 3 demonstrated that individuals with both natural driving experience and racing video game experience exhibit an "optimal" gaze behaviour pattern. This pattern is associated with superior performance compared to the two other groups, drivers who do not play video games and gamers who do not drive. In this context, optimal gaze behaviour is characterized by an increased number of fixations on task-relevant information sources, indicating enhanced goal-directed attentional control (ALLSOP et al., 2016).

In Chapter 4, drivers with Parkinson's disease (PD) showed increased occurrence of collisions and difficulties maintaining speed compared to younger drivers. While both PD drivers and older adults performed worse than younger drivers overall, there was no significant difference between PD drivers and older adults in driving performance. Nevertheless, older drivers tended to restrict their gaze fixations to the lane area to detect potential hazards, whereas PD drivers displayed a more random gaze pattern, suggesting differing attentional control between the groups. Although gaze behaviour measures have been widely utilized as guides to discovery in traffic navigation research (see review of LAND, 2006; MAHANAMA et al., 2022), it can be argued that they are somehow decoupled from driving performance. According to model-based approaches, visual perception involves the brain interpreting visual stimuli received during gaze fixation (LAND, 2006a). Therefore, visual perception implies attentional engagement. Gaze behaviour is then the bond between perception and attention, and it can be understood as an indirect measure of visual attention.

In the second part of this thesis, I adopted an ecological perspective, utilizing affordance-based control as the guide of discovery to examine the visual control of braking in cycling. Chapter 5 revealed that cyclists use an affordance-based control strategy for braking, regardless of cycling experience. Participants avoided collisions by making adaptative brake adjustments that keep ideal deceleration (required action) below the maximum achievable deceleration (maximum action capabilities). Additionally, more experienced active cyclists were more likely to exhibit an aggressive braking style, which involves starting to brake later and applying a higher, steeper peak in deceleration compared to less experienced cyclists, who tended to brake earlier and show more gradual deceleration. I suggested that the braking styles emerge from differences in calibration between information and action. Furthermore, Chapter 6 provided additional evidence supporting the hypothesis that braking in cycling is guided by affordances. Cyclists initiated braking earlier and with lower deceleration on downhill slopes. However, this slope-related effect disappeared when ideal deceleration was scaled to maximum deceleration, though not to preferred deceleration. Interestingly, braking styles similar to those described in Chapter 5 were observed. In the uphill conditions, cyclists tended to perform a more aggressive braking compared to the downhill slope. Differences in brake adjustment magnitudes between styles disappeared when ideal deceleration was scaled to maximum deceleration.

The affordance-based control approach focuses on measuring the perception-action coupling through intrinsic variables such as body-scaled and action-scaled information, rather than relying on extrinsic metrics like Cartesian distance. For example, when approaching an aperture, individuals perceive the possibility of passing through it by detecting the aperture width relative to their shoulder width. Hence, ecological studies on affordance perception in crossing apertures utilize body-scaled metrics such as the A/S ratio (aperture width to shoulder

width). This ratio informs the individual whether an aperture is passable or impassable (HIGUCHI et al., 2011; WAGMAN et al., 2016; YASUDA et al., 2014). Similarly, in Chapters 5 and 6, our results show that the ideal deceleration specifying time-to-contact is detected in units of maximum achievable deceleration (i.e., Dideal in % Dmax). This action-scaled information directly informs the cyclist whether it is possible or impossible to stop in time.

Gaze behaviour and affordances perception

As previously explored, the affordance-based approach highlights the direct perception of affordances. FAJEN (2007) clarifies that affordances are "invisible", implying that information variables that specify affordances are different than those that specify how to move to perform a task, i.e., specifying optical invariants. This raises questions about the role of gaze behaviour in perceiving affordances. Traditionally, gaze fixations have been associated to the time required for internal model/information processing and action execution programming (LAND, 2006; UNDERWOOD et al., 2003; VICKERS, 1997). However, from an ecological perspective, perception operates without explicit cognitive processing. So, how do we explain prolonged fixations on relevant AOIs associated with task success (e.g., Quiet Eye, as elucidated in the work of J. VICKERS, 1997)? Despite growing interest in gaze behaviour and affordances, this area remains relatively underexplored among ecological researchers.

From an ecological perspective, the examination of gaze behaviour encompasses at least two critical considerations. First, the fixation-saccade strategy is controlled so as to detect task-specific optical variables within the optical flow. According to WITHAGEN and MICHAELS (2005), functional systems should not be regarded as mere anatomical structures or assembled devices; instead, they are best understood as capabilities - the ability of animals to establish functional relations with their environment. For example, consider the tau-dot when approaching a stationary obstacle. This optical variable can be detected through various means: i) by using the radial retinal flow generated when the eyes fixate the stationary obstacle; ii) by shifting fixations between near-road and far-road points; iii) or even by fixating on another environmental point while keeping the obstacle within peripheral vision. Consequently, vision is conceptualized as an ability; even a blind person possesses a visual cortex and retina, although lacking the ability to pick up optical variables (but with support perhaps still able to perceive approaching objects, (BACH-Y-RITA et al., 1969). Thus, in identifying optical variables within the optic flow, various gaze behaviour patterns may be employed to facilitate the act of perception. DICKS and colleagues (2017) investigated how different gaze patterns contribute to successful performance in sports. Their study highlights that individuals can achieve the same performance outcomes using different gaze patterns, suggesting there is no single "optimal" gaze strategy for all performers (DICKS et al., 2017). Consistent with this idea, different gaze patterns can serve as exploratory movements to achieve the same outcome, a concept known as degeneracy (SEIFERT et al., 2021).

Second, gaze behaviour patterns may vary among individuals, reflecting differences in experiences, skill or styles of control. Our research, as detailed in chapters 5 and 6, identified distinct braking styles among cyclists, all resulting in successful outcomes. This suggests that different individuals may also adopt diverse styles to pick-up optical variables within the optic flow. These variations in the patterns of gaze can be influenced by factors such as expertise

level, task complexity, and environmental conditions. For instance, studies have shown that expert cyclists tend to employ more goal-directed patterns compared to novice cyclists (VANSTEENKISTE et al., 2013, 2014). Additionally, the nature of the task itself can dictate the preferred gaze pattern; for example, navigating through dense traffic may require a different pattern of gaze than riding on an open road (VANSTEENKISTE et al., 2013). During the study reported in Chapter 5, I also recorded cyclists' gaze behaviours. Upcoming analyses will help me deepen understanding of how gaze behaviour is coordinated within affordance-based control of action, also offering more generic insights into the intricate dynamics of human-environment interaction. As such, while the relationship between gaze behaviour and affordances remains relatively underexplored, it represents a promising route for future research in ecological studies.

The shift in the theoretical framework and guides to discovery in this thesis signifies not only the adoption of different concepts and methodologies but also a profound change in ontological perspective. In affordance-based control, concepts such as "internal models" and "information processing" do not exist. Conversely, cognitive psychologists might use the term affordances to unequivocally refer to "potential actions"; however, affordances, in the ecological sense, is absent within the cognitive ontology (CHEMERO, 2009; DE WIT et al., 2017; FAVELA, 2024). By transitioning from a cognitivist approach to an ecological perspective, the focus moves from understanding internal cognitive processes to examining the direct perception-action, organism-environment coupling. This has significant implications for research in traffic navigation. The move towards an affordance-based control approach opens up new avenues for understanding complex behaviours in real-world, in-situ settings.

7.2. Affordances: the answer to all our problems?

The findings presented in this thesis contribute to our understanding of visually guided actions in traffic navigation through the lens of affordance-based control. Chapters 5 and 6 provide evidence supporting the hypothesis that the visual control of braking in in-situ cycling is affordance-based. This finding is consistent with previous research, including studies on braking (FAJEN, 2005c, 2005a, 2007, 2008; RUGINSKI et al., 2019) and overtaking (MORICE et al., 2015) in simulated driving, walking on complex terrain (FAJEN, 2013; MATTHIS et al., 2017, 2018; MATTHIS; FAJEN, 2013) and stopping penalty kicks in football (ZHENG et al., 2021, 2022). FAJEN's (2007) affordance-based approach shows that information-based control approach is insufficient to account for one's action capabilities. However, unlike information-based models (ANDERSEN et al., 1999; LEE, 1976), FAJEN did not provide a law of control that explains how affordances perception guides action (HARRISON et al., 2016).

Efforts to model affordance-based control have been undertaken by researchers such as HARRISON et al. (2016) and VAN DER KAMP et al. (2018). VAN DER KAMP et al. (2018) proposed a control law for the stopping of penalty kicks in football, supported by evidence from ZHENG et al. (2021). The findings in Chapter 6 advance this work by applying the affordance-based control law proposed by VAN DER KAMP et al's (2018) for the penalty kick to the visual control of braking in cycling.

Fig. 27

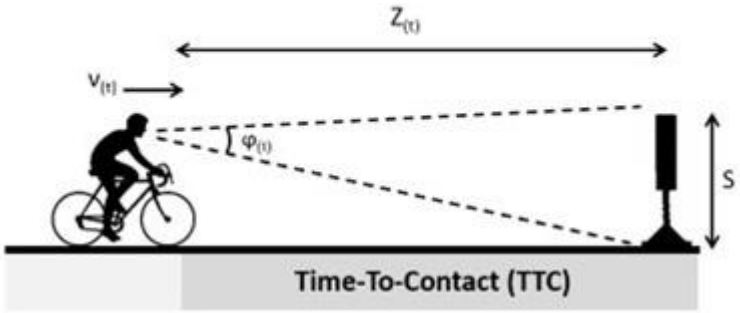


Figure 27: Variables describing a cyclist approaching an obstacle: obstacle size (S), distance from the object as a function of time (Z(t)), the cyclist's velocity as a function of time (V(t)), and the optical angle of the obstacle as a function of time (ϕ(t)).

Consider the task of braking to avoid collision in cycling and Lee's (1976) *tau-dot* control strategy (see Figure 8). In this context, the ideal deceleration (Dideal) represents the ideal state which the individual should strive to be at any moment (FAJEN, 2007). The calculation of Dideal is expressed as follows:

$$D^*_{ideal} = \frac{v^2}{2Z} = \frac{GOFR}{2\tau} \tag{6}$$

where v refers to current velocity and Z denotes the current distance to the obstacle. The Global Optic Flow Rate ($GOFR$) is defined as the rate of optical motion of texture elements, while τ, specifies the time-to-contact (Fajen, 2005a). Dideal is derived from *tau-dot* (see details in chapter 1, p. 13). In the affordance-based control strategy (FAJEN, 2007), successful braking is achieved by maintaining the Dideal within one's action boundaries. Therefore, we utilize D^*_{ideal} to indicate that the required or ideal deceleration is measured in proportion of maximum achievable deceleration. This concept can be outlined in this law of control:

$$\begin{matrix} if\ D^*_{ideal} < 1, braking\ is\ possible \\ if\ D^*_{ideal} > 1, braking\ is\ impossible \end{matrix} \tag{7}$$

When the required or ideal deceleration is below the maximum achievable deceleration (i.e., $D^*_{ideal} < 1$), bringing the bicycle to a stop is afforded and the cyclist perceives the bicycle as stoppable. However, when the required or ideal deceleration exceeds maximum achievable deceleration (i.e., $D^*_{ideal} > 1$), stopping the bicycle becomes impossible. According to this law of control, information is scaled to action, in contrast to the *tau-dot* strategy. Consequently, brake adjustments are executed to maintain the required or ideal deceleration within the

maximum achievable deceleration. In other words, the cyclist must brake such as to maintain the perception that the bicycle is stoppable (FAJEN, 2007; VAN DER KAMP et al., 2018a).

The findings in Chapter 6 indicate that cyclists perform brake adjustments relative to maximum deceleration rather than their preferred deceleration, thereby confirming the hypothesis that information is scaled to the maximum action boundary. This lends strong support to affordance-based approach and the law of control described above (FAJEN, 2005c, 2005a; FAJEN et al., 2011; RUGINSKI et al., 2019; ZHENG et al., 2022). Chapter 5 assessed the maximum achieved deceleration, determined by the highest peak of current deceleration. This measurement only captures the current maximum deceleration but fails to account for the maximum achievable deceleration. Chapter 6 overcame this limitation by using a maximum braking test that allowed us to investigate action scaling in braking towards the maximum achievable deceleration. To our knowledge, our research is pioneering in providing evidence that support a law of control based on the individual's action capabilities, aligning with FAJEN's (2007) affordance-based approach. Furthermore, the model proposed by FAJEN (2007) presented its initial evidence in studies carried out in a virtual environment within laboratories. Thus, this thesis advances our understanding of visually guided actions in in-situ navigation.

7.3. Final points of consideration

In the current thesis, braking tasks were isolated on purpose to minimize distractions and prioritize participant safety. The term "in-situ," derived from Latin, denotes experiments conducted within the natural context of the phenomenon under investigation, as opposed to artificial environments (in vitro) (ARAÚJO et al., 2007). Our studies in chapters 5 and 6 are categorized as in-situ due to their utilization of a real bicycle and tasks closely resembling real-world braking scenarios. However, for ethical reasons, cyclists were not exposed to the real traffic situation. Future investigations could explore braking behaviours in more complex settings, such as winding roads or intersections, or recording in real traffic with other traffic users, to broaden our understanding. Unlike the driving simulation tasks in chapters 2, 3, and 4, the in-situ cycling experiments in chapters 5 and 6 solely focused on braking. In actual traffic settings, this is only one of the many tasks that drivers/cyclists have to deal with. Nevertheless, these studies offer valuable insights into how braking is regulated by affordances. Future research should integrate braking with steering tasks, crossing static gaps (e.g., in between two poles) or dynamic gaps (e.g., in between approaching cars) to comprehensively explore visually guided actions of road traffic users.

The strength of the thesis lies in utilizing diverse theoretical frameworks to the understanding of visual perception in guiding actions of drivers and cyclists. Various methodologies were employed to assess perceptual-motor behaviour, including linear and non-linear analyses of gaze behaviour. The application of visual entropy to study attentional control represents a significant advancement in the field, with potential applications for the identification of risky gaze behaviour (e.g., under pressure) for enhancing road safety. Similarly, by examining cyclists' braking behaviour through action-scaled variables I opened the door to a fruitful avenue for research. Furthermore, the current thesis demonstrates a

commitment to ecological validity, emphasizing the relevance of our findings to real-world contexts. This work suggests that the affordance-based approach, proposed by FAJEN (2007), enriches investigations of visually guided actions, particularly in traffic research, where efficient navigation relies on perceiving the environmental opportunities for action.

Although the primary purpose of this thesis was to investigate the visually guided actions of urban traffic users through the lens of different theoretical frameworks, the findings reveal practical insights for driving and cycling. Drivers' and cyclists' attentional control is crucial to prevent accidents, including the ability to predict other road users' behaviour (e.g. anticipating gaps that affords crossing). Our studies indicate that incorporating driving simulators into training programs can benefit inexperienced drivers by allowing them to practice handling high-stress situations. This approach also holds promise for elderly drivers, including those with Parkinson's disease, offering them a controlled environment to enhance their real-world driving skills. By revealing the differences in gaze behaviour between experienced and inexperienced drivers, as well as gamers who intend to become drivers, the current thesis highlights the importance of incorporating stress management techniques into driver training programs. Additionally, car manufacturers could design dashboards that minimize distractions, particularly for inexperienced drivers who tend to focus on threatening stimuli rather than task-relevant information. Finally, chapter 4 informs policymakers about the specific challenges faced by PD and elderly drivers, potentially leading to revised guidelines for driver assessments and licensing to ensure road safety for all users.

In cycling, our findings highlight the importance of perceiving affordances for successful braking. By showing that cyclists use an affordance-based control of braking, our findings suggest that training programs can be designed to help inexperienced cyclists such as children and/or inactive adult cyclists better perceive and act within their braking capabilities. For example, exposing cyclists to bicycles of varying weights and riding on inclines or declines would allow them to perceive how braking capabilities change dynamically. Additionally, training in complex terrains such as forests, heavy traffic, and slippery surfaces can offer valuable practical experience, though safety should not be neglected. Particularly, chapter 5 showed that the positioning and weight of loads on a bicycle may affect braking performance. This insight can guide the design of safer bicycles and accessories, ensuring that added weights do not compromise braking efficiency. Finally, our findings reveal that more experienced cyclists tend to adopt a more aggressive style of braking, suggesting that training programs could focus on helping less experienced cyclists improve their braking skills and confidence, thereby enhancing overall road safety.

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Supplementary Materials

S.1. Further analysis of Chapter 2 data

Published as:
G. Gotardi, M. Navarro, P. Polastri, P. Schor, D. Orth, R. Oudejans, J. van der Kamp, G. Savelsbergh, and S. Rodrigues. 2018. The influence of anxiety on visual entropy of experienced drivers. In Proceedings of ETRA Symposium, Warsaw, Poland, June 2018, 3 pages. DOI: https://doi.org/10.1145/3205929.32059

Gaze Entropy calculation

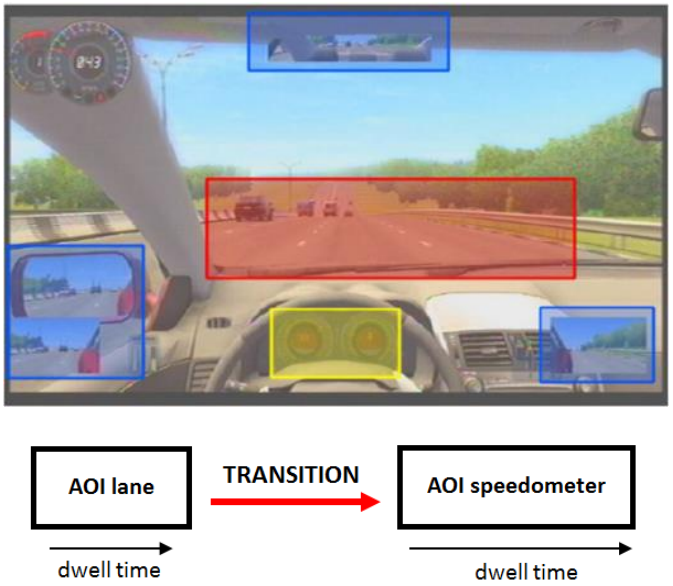


Figure S1: a) Areas of Interesse (AOI)s used in the entropy calculation: lane (red), speedometer (yellow) and rearview mirrors (blue); b) Given example of fixation transition 'from' lane 'to' speedometer. Dwell time represents glance duration in each AOI.

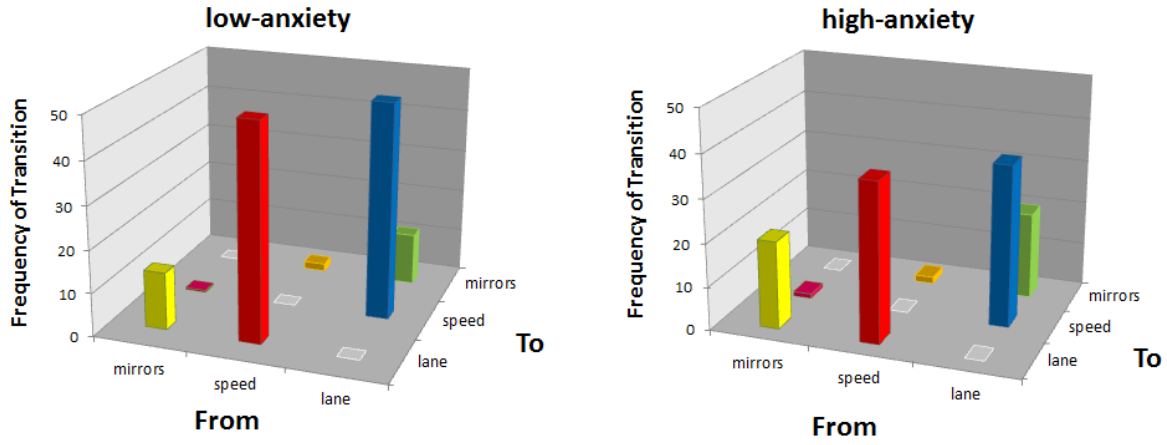


Figure S2: Frequency of transitions between AOIs in both experimental conditions. Transitions within the same AOI were excluded (zero).

Entropy calculation follows the same equation of chapter 4.

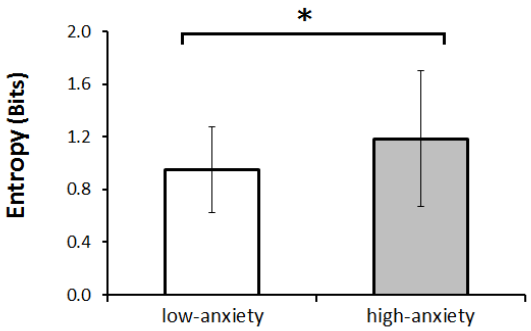
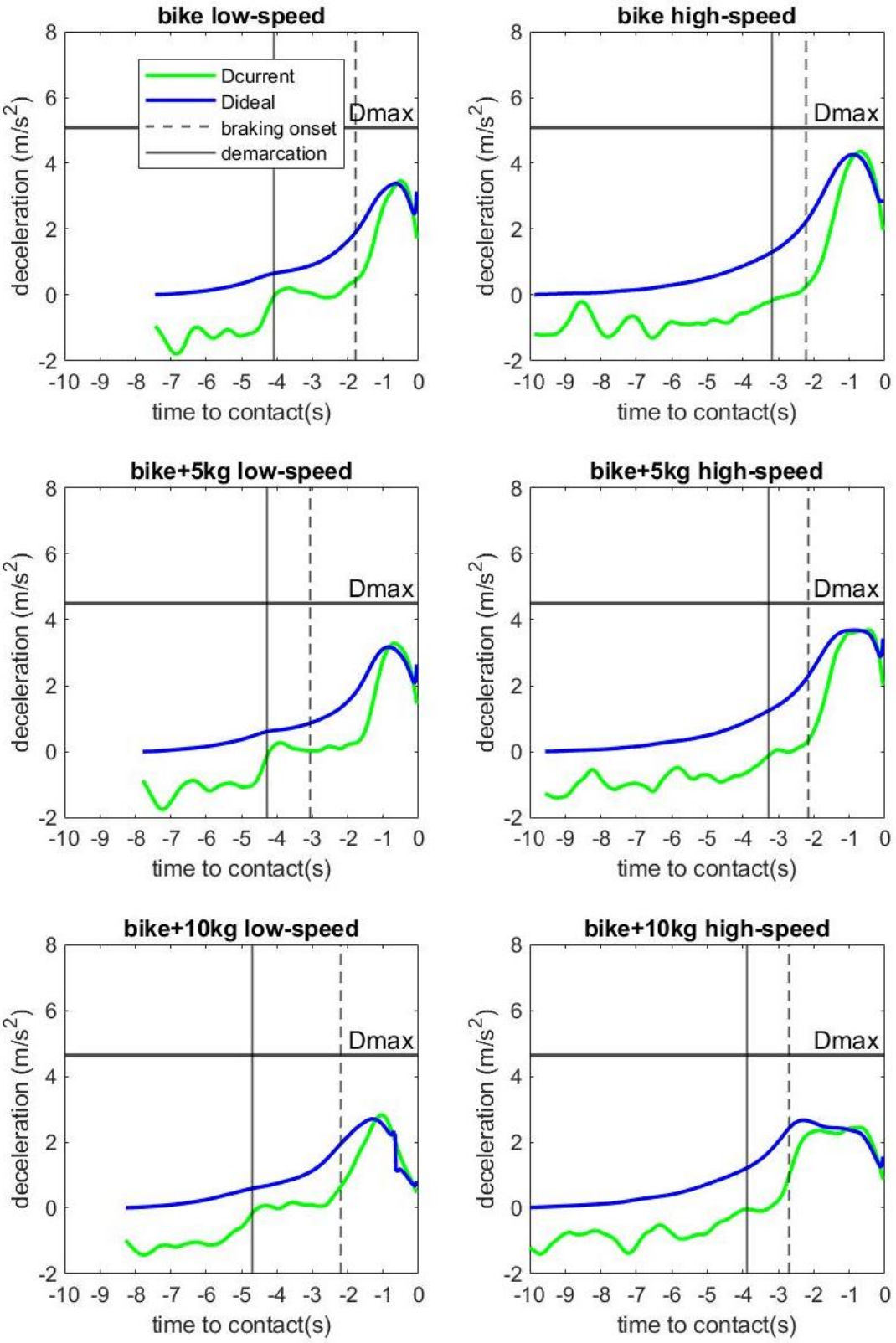
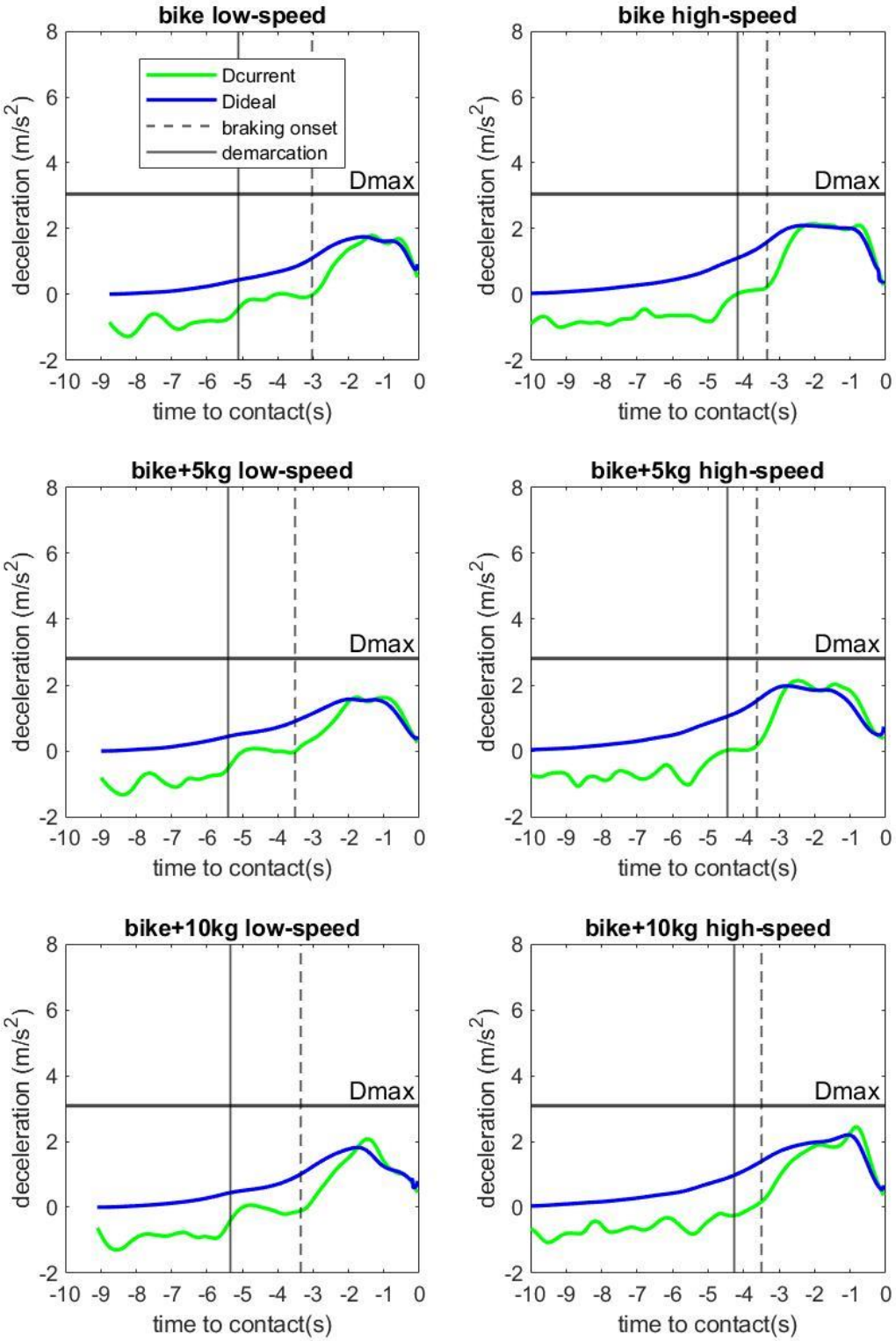


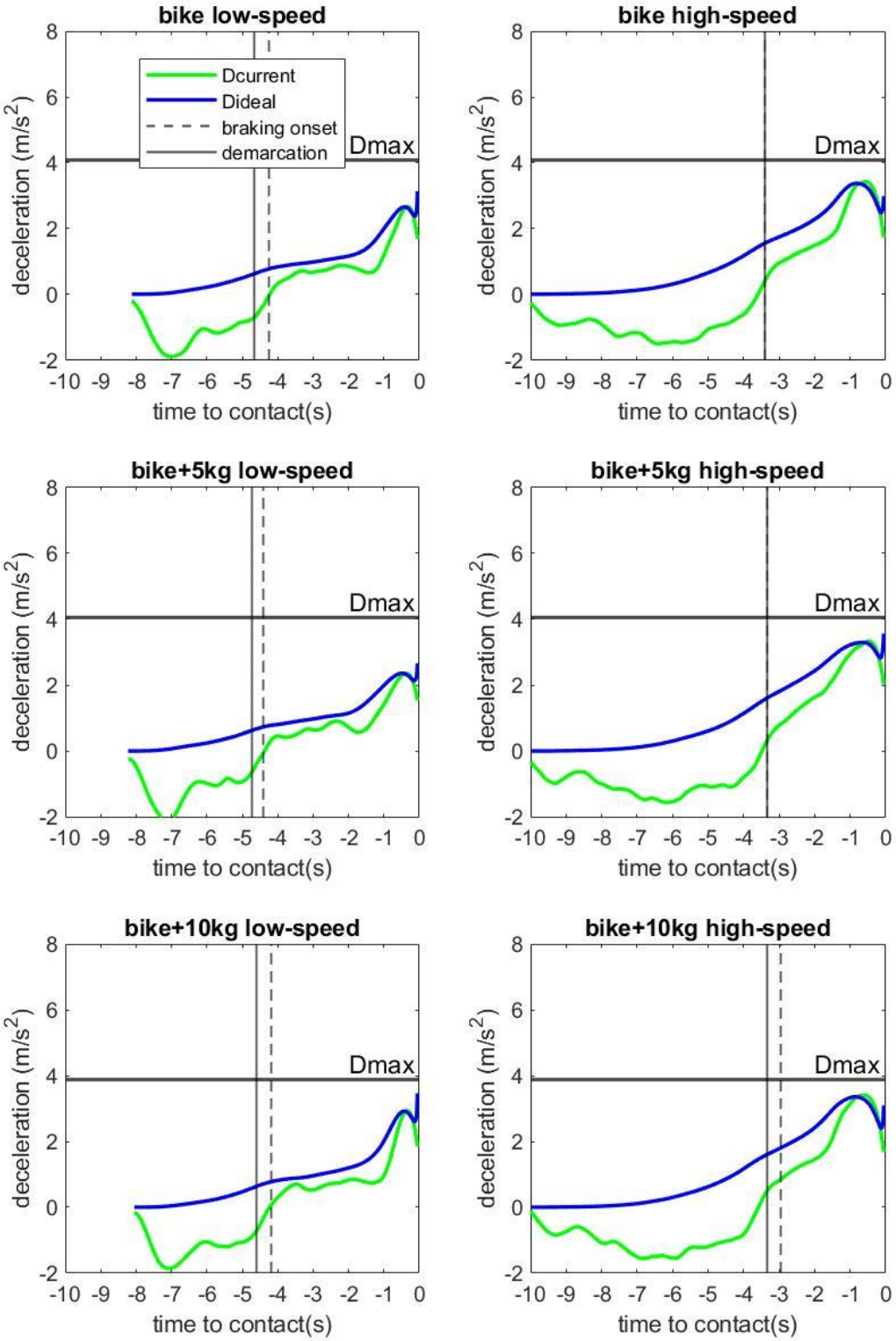
Figure 4. Relative entropy in both experimental conditions.

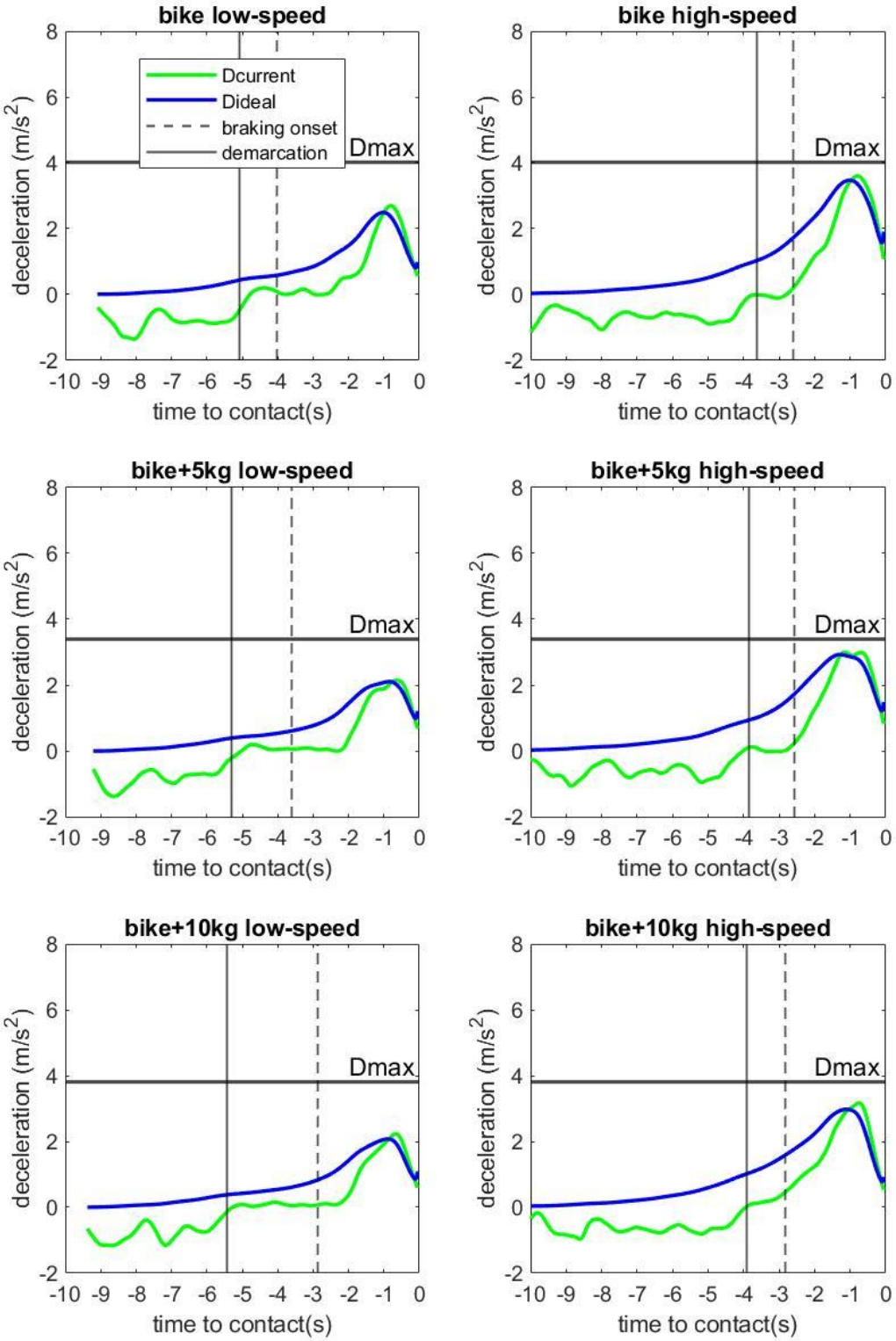
S.2. Plots for braking styles classification of Chapter 5 data

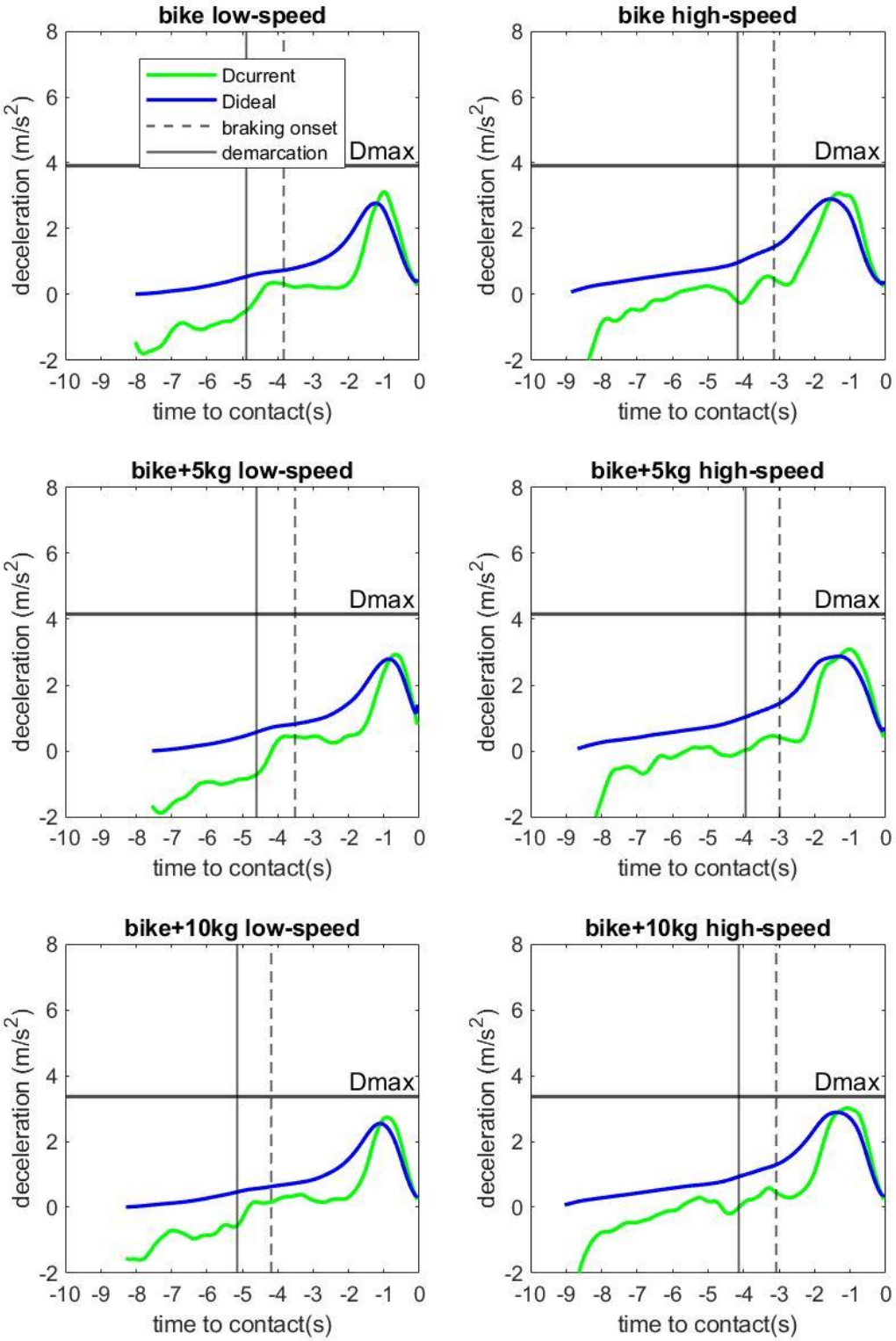
For each participant, six plots – one for each experimental condition – are presented.

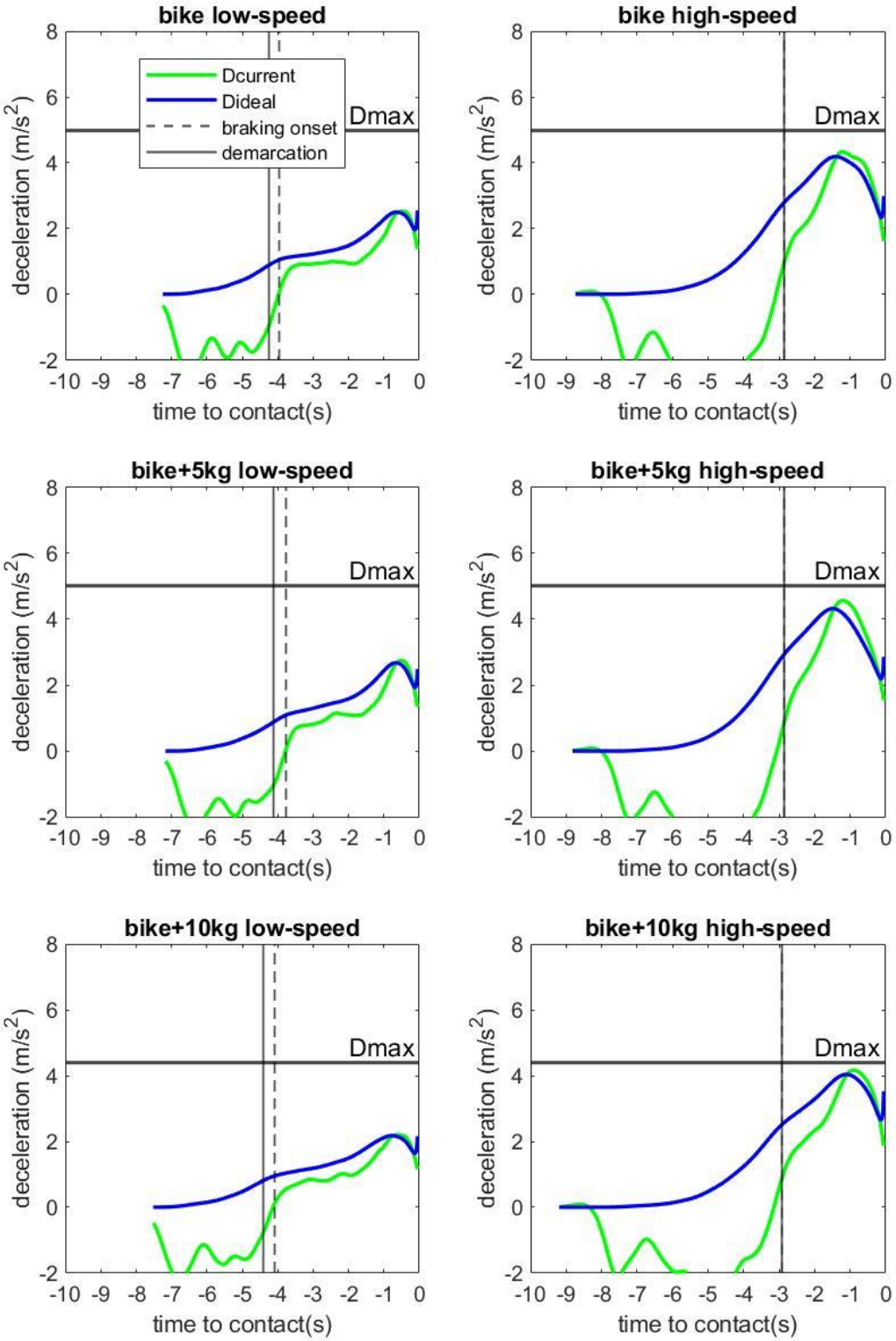


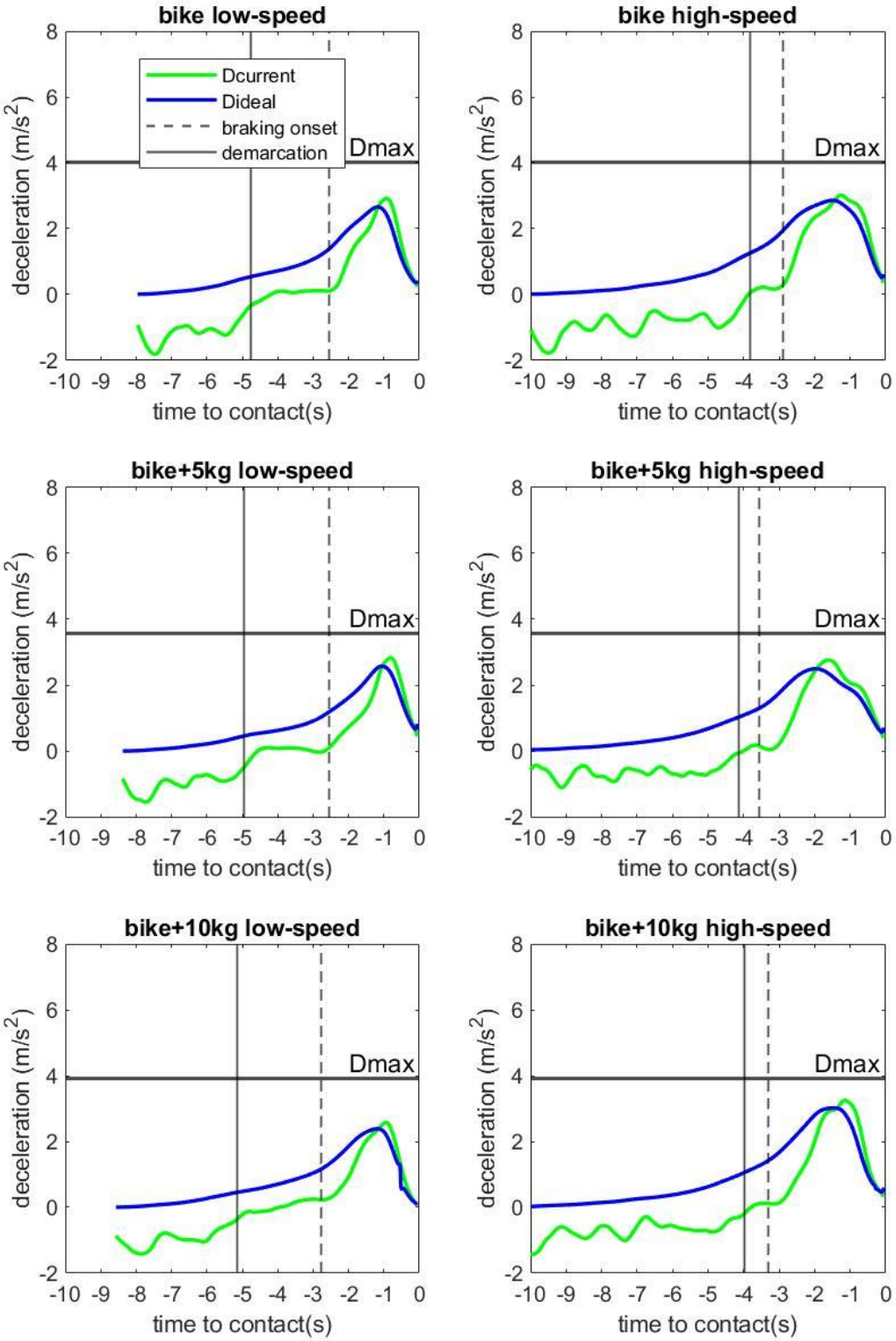

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s^2)
time to contact(s)
8
6
4
2
0
-2
-10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0

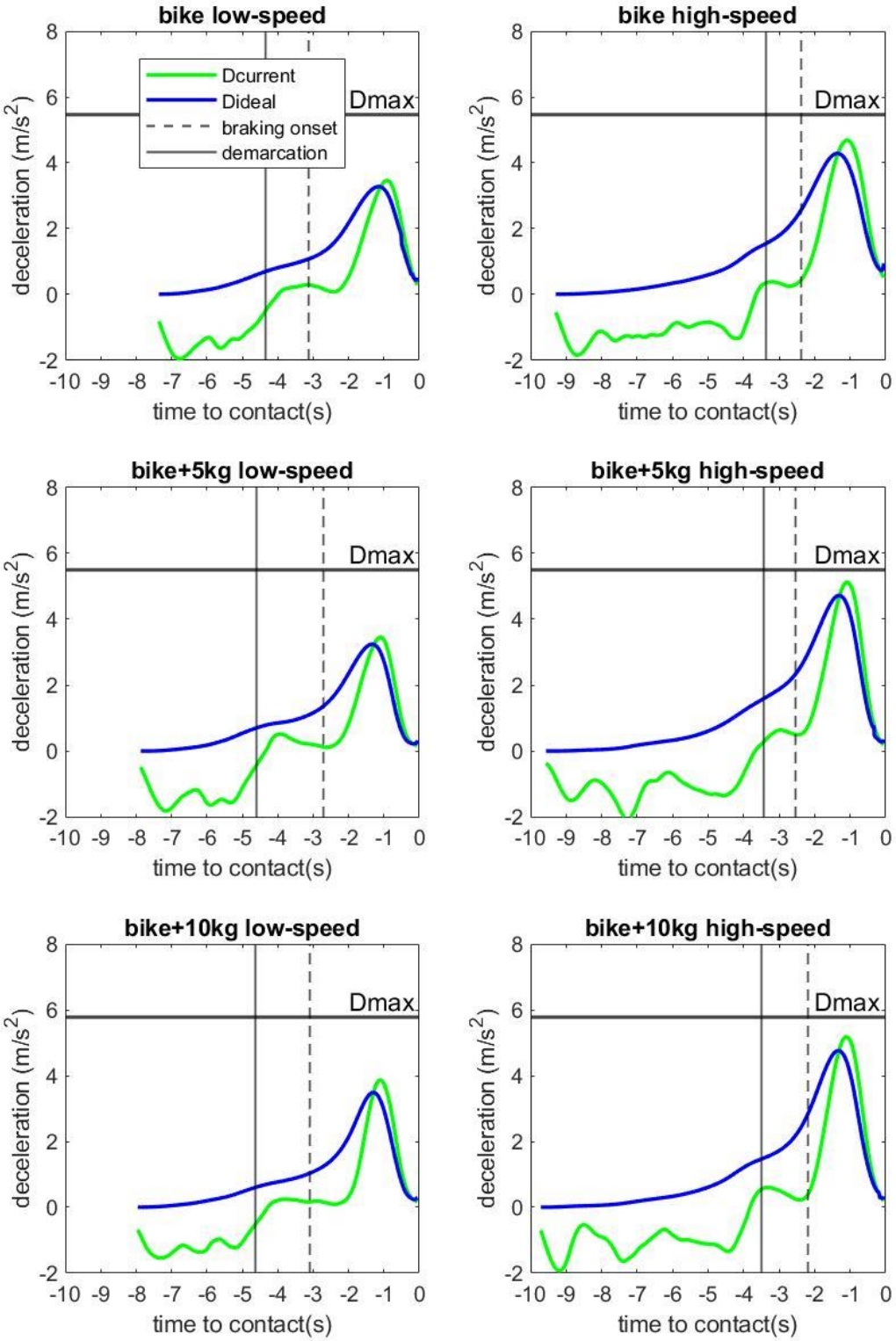

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s2)
time to contact(s)

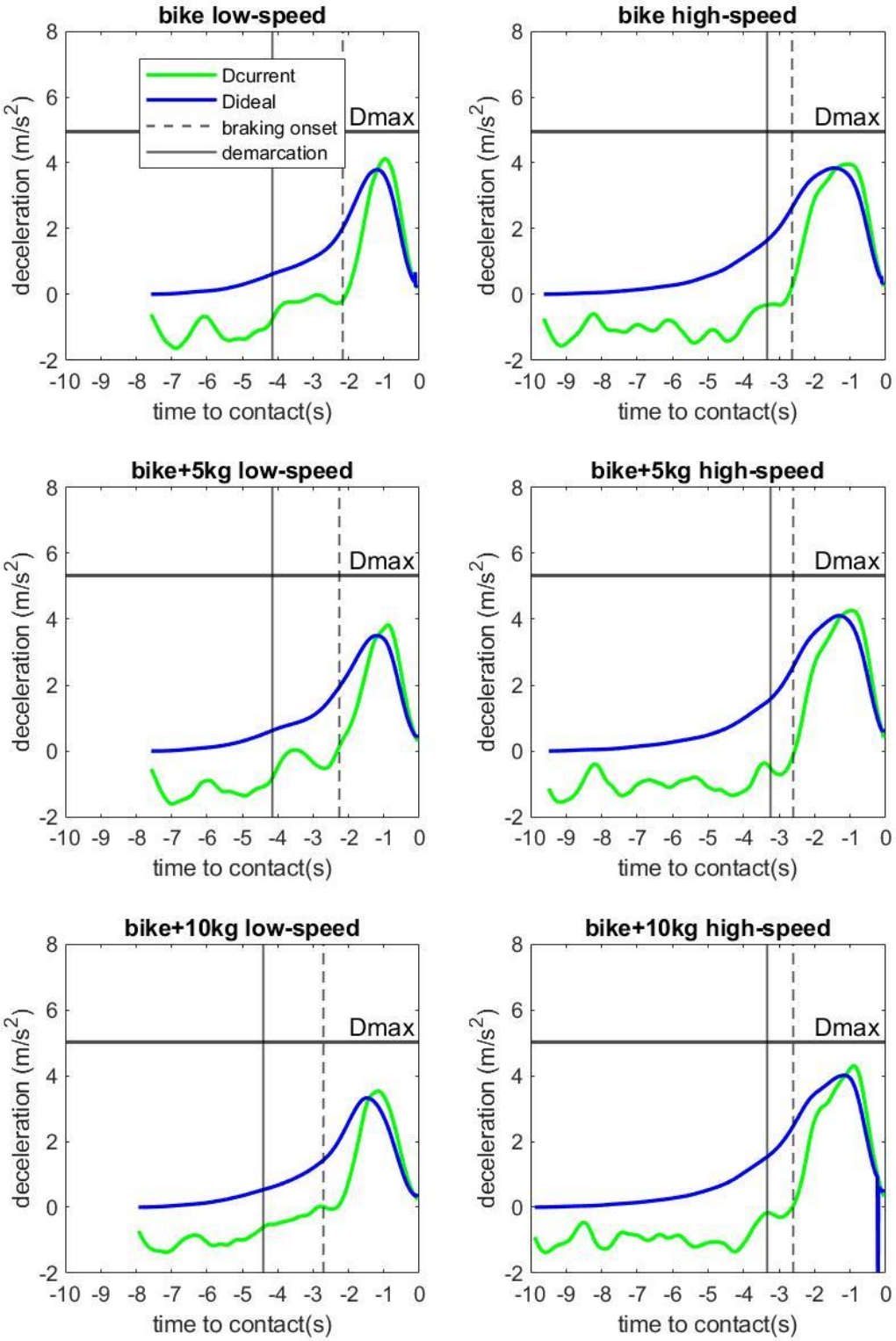

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s^2)
time to contact(s)

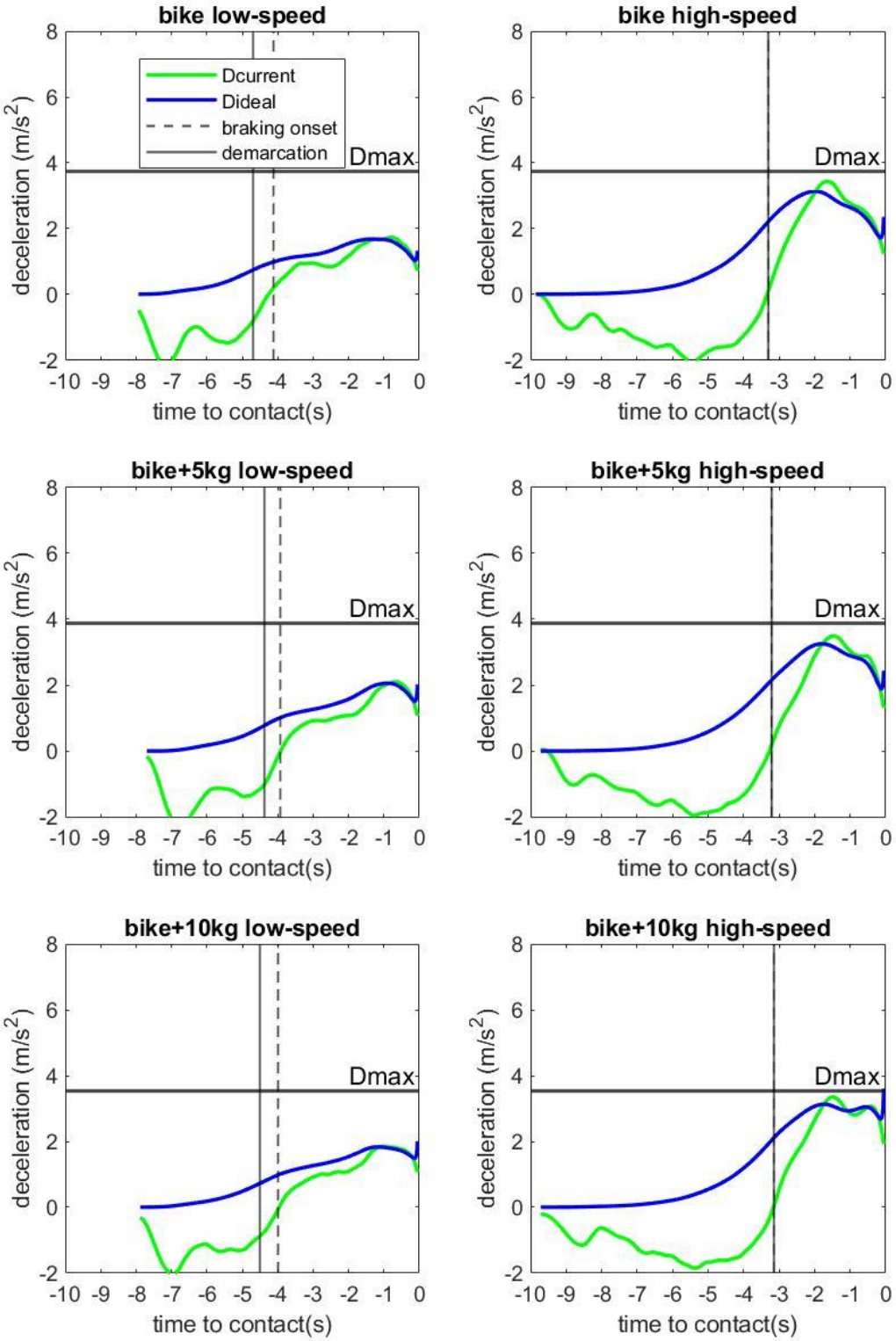

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s2)
time to contact(s)

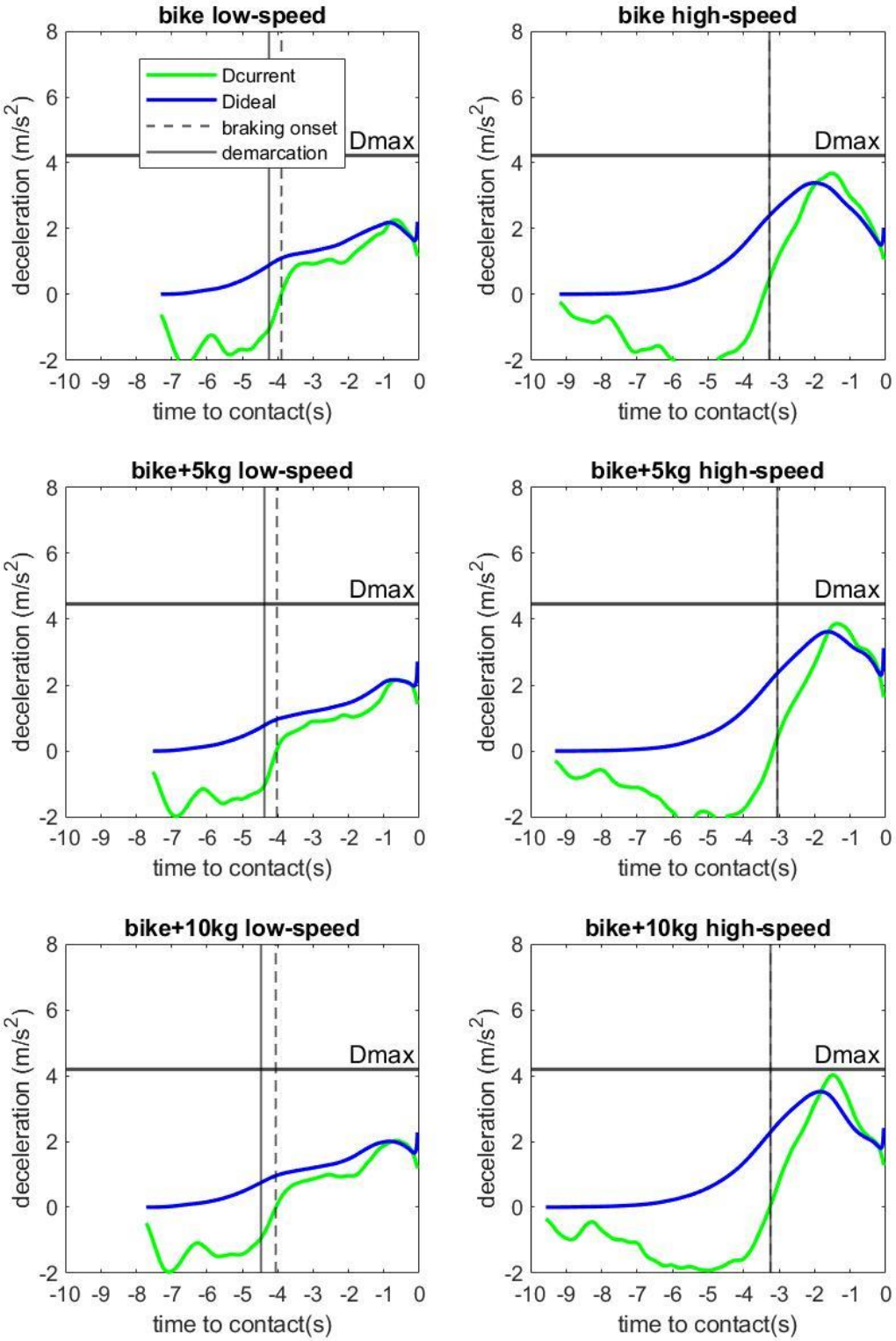

bike low-speed
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bike+5kg low-speed
bike+5kg high-speed
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bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s^2)
time to contact(s)

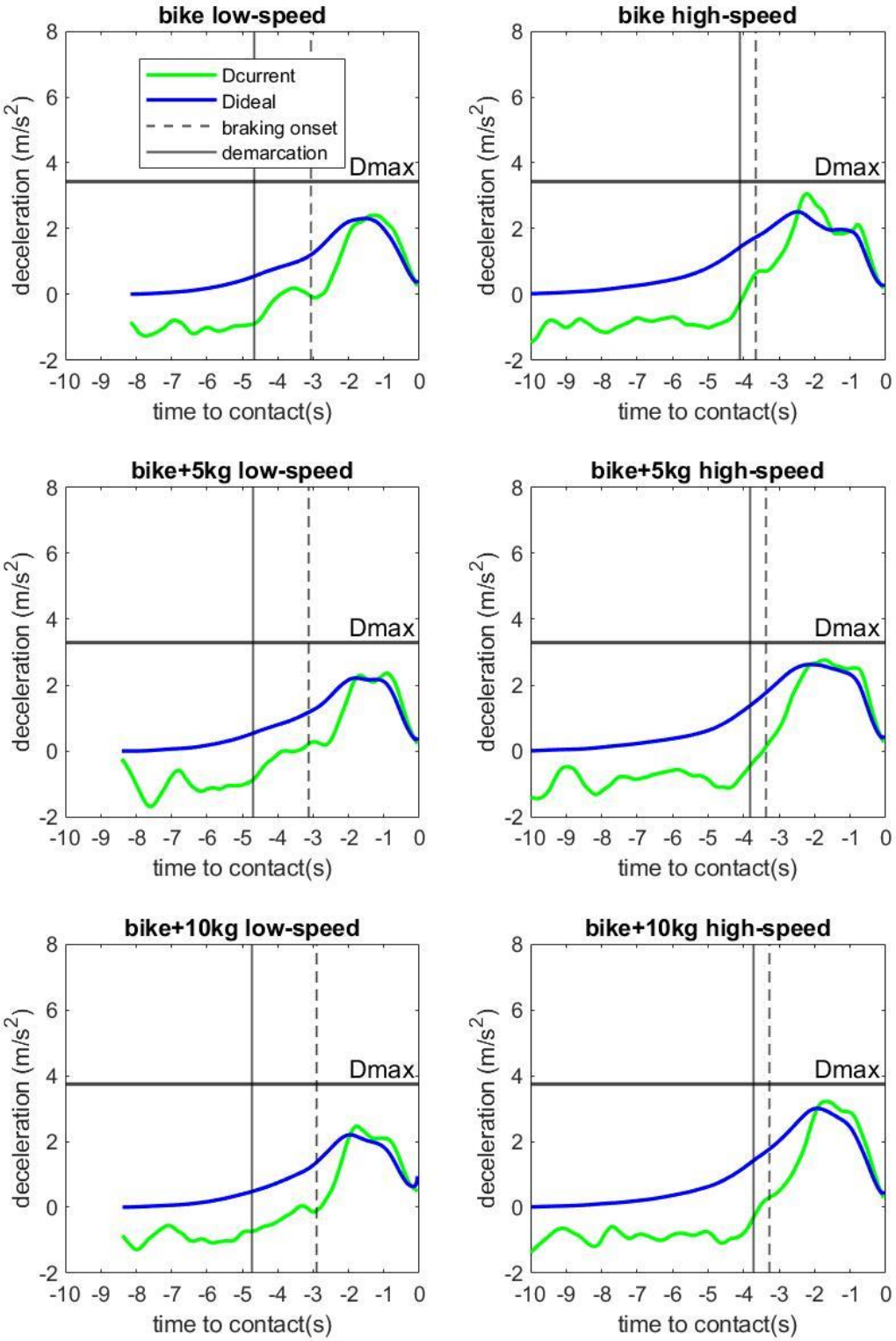

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bike high-speed
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Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s2)
time to contact(s)

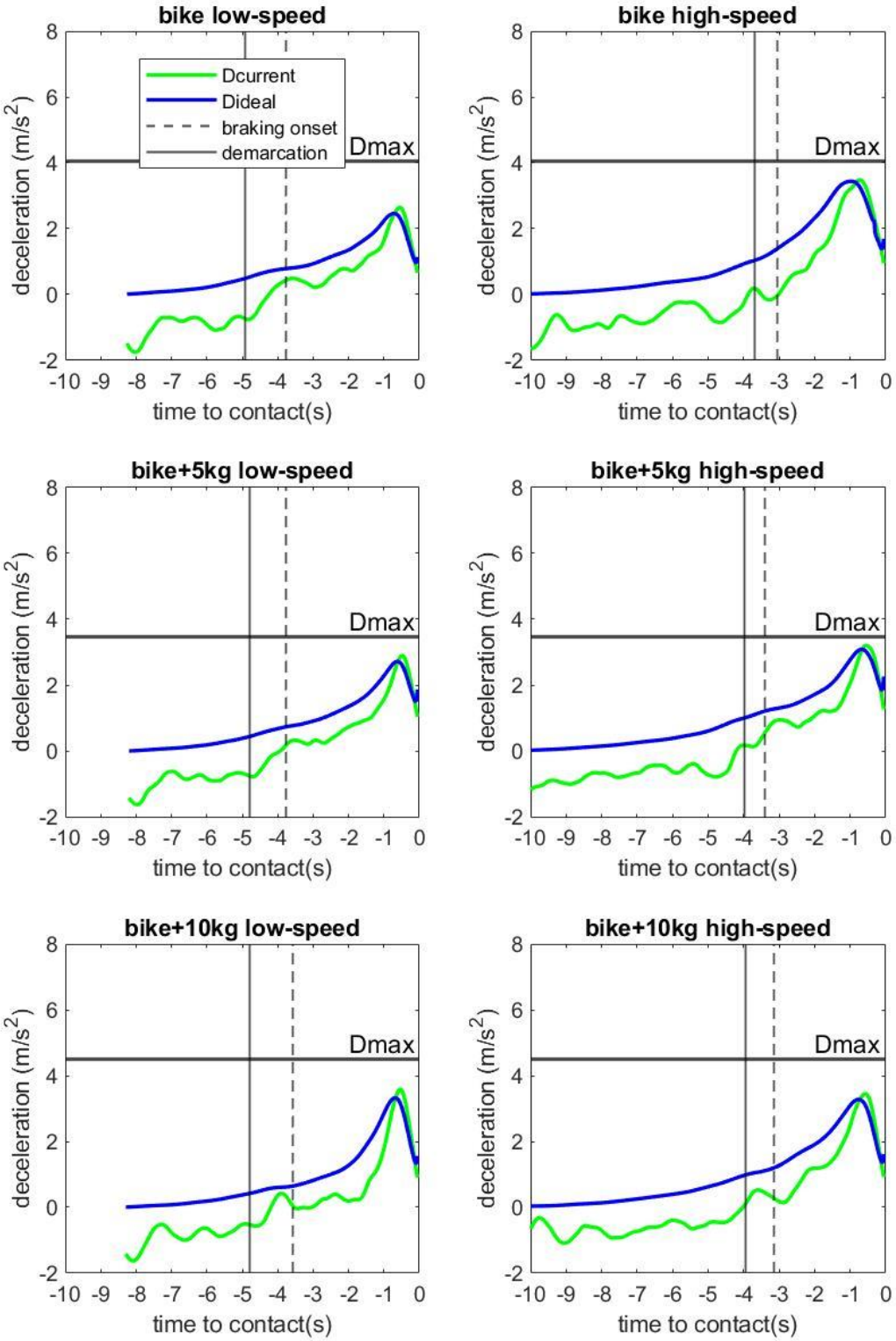

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Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s^2)
time to contact(s)

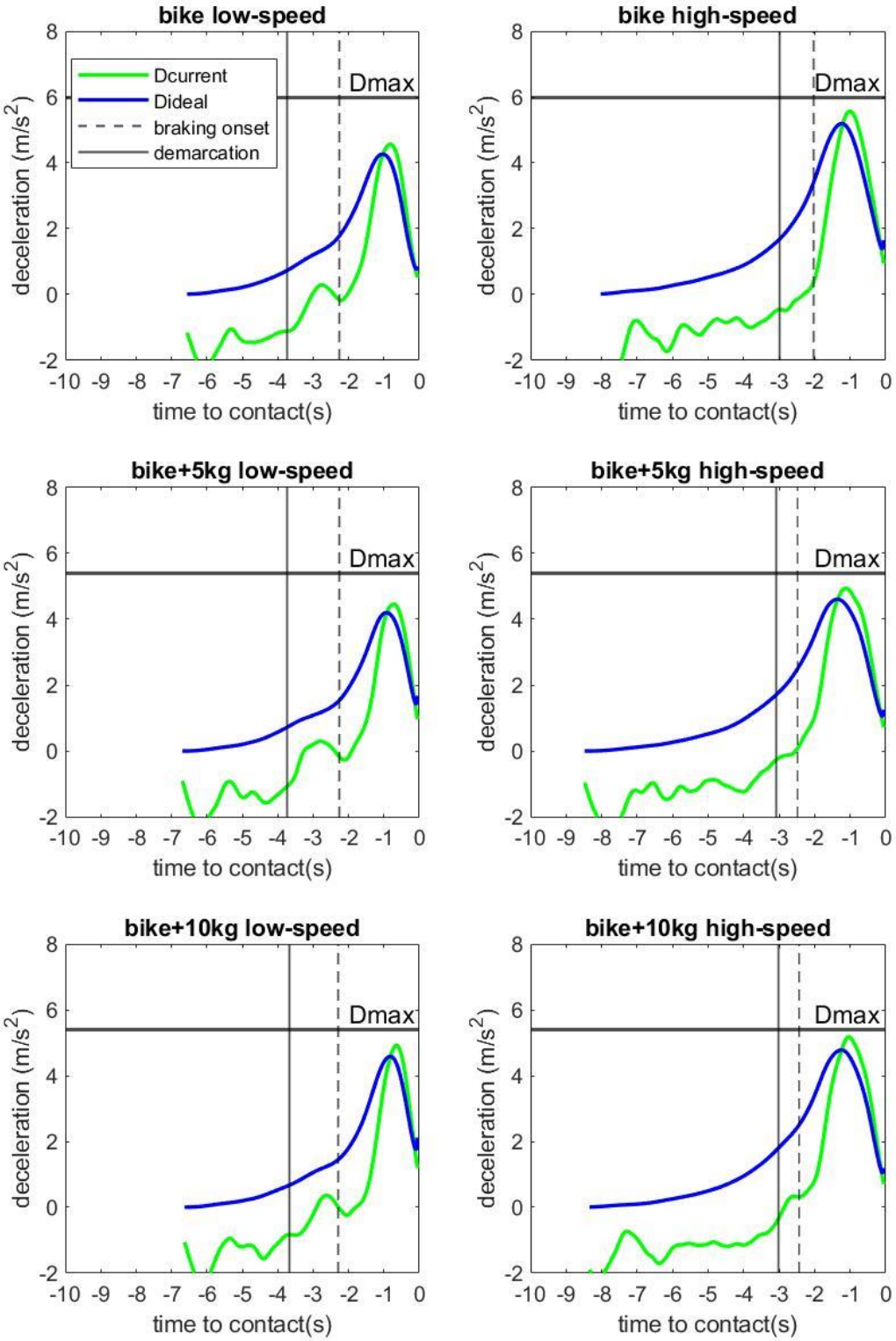

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s2)
time to contact(s)

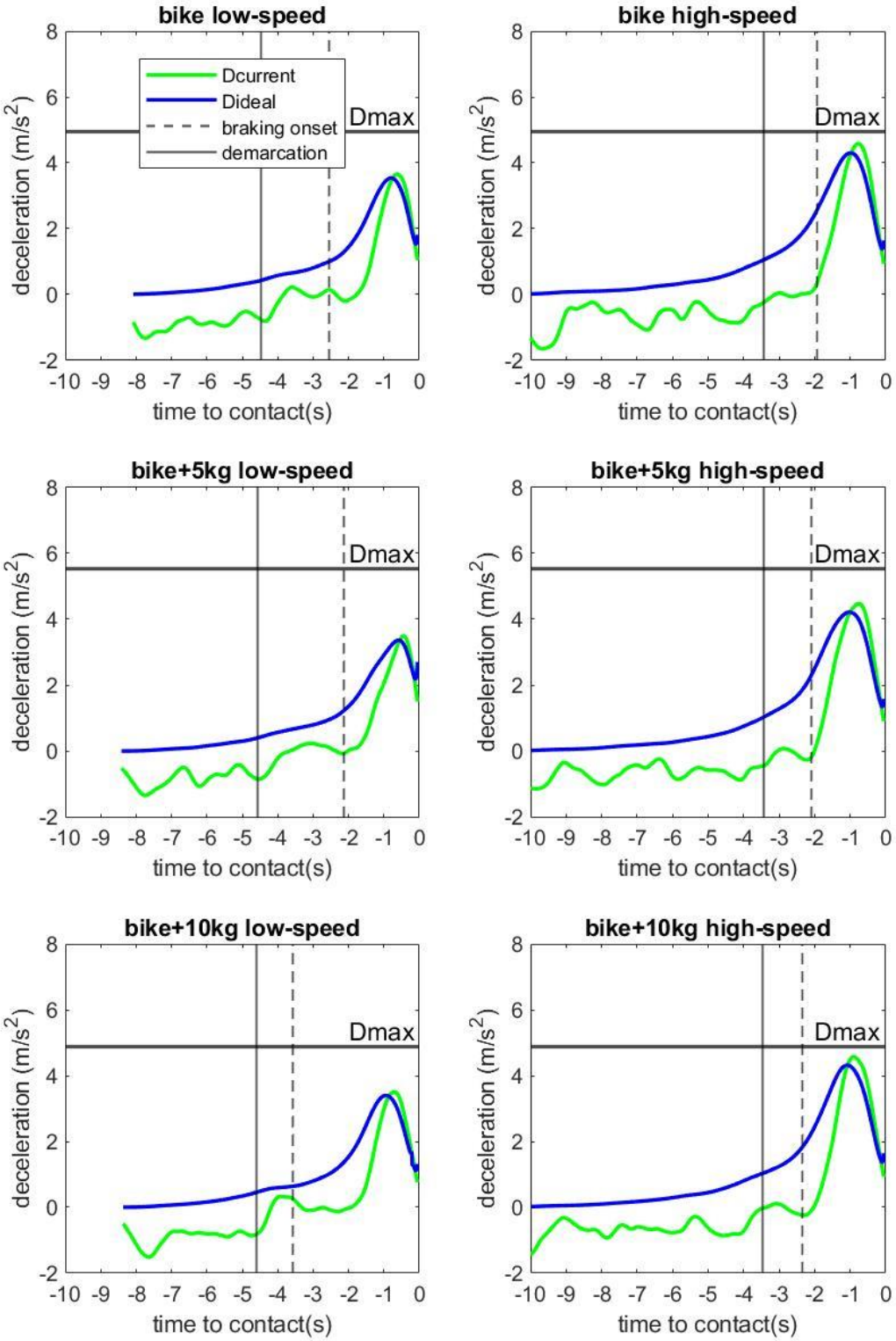

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s2)
time to contact(s)

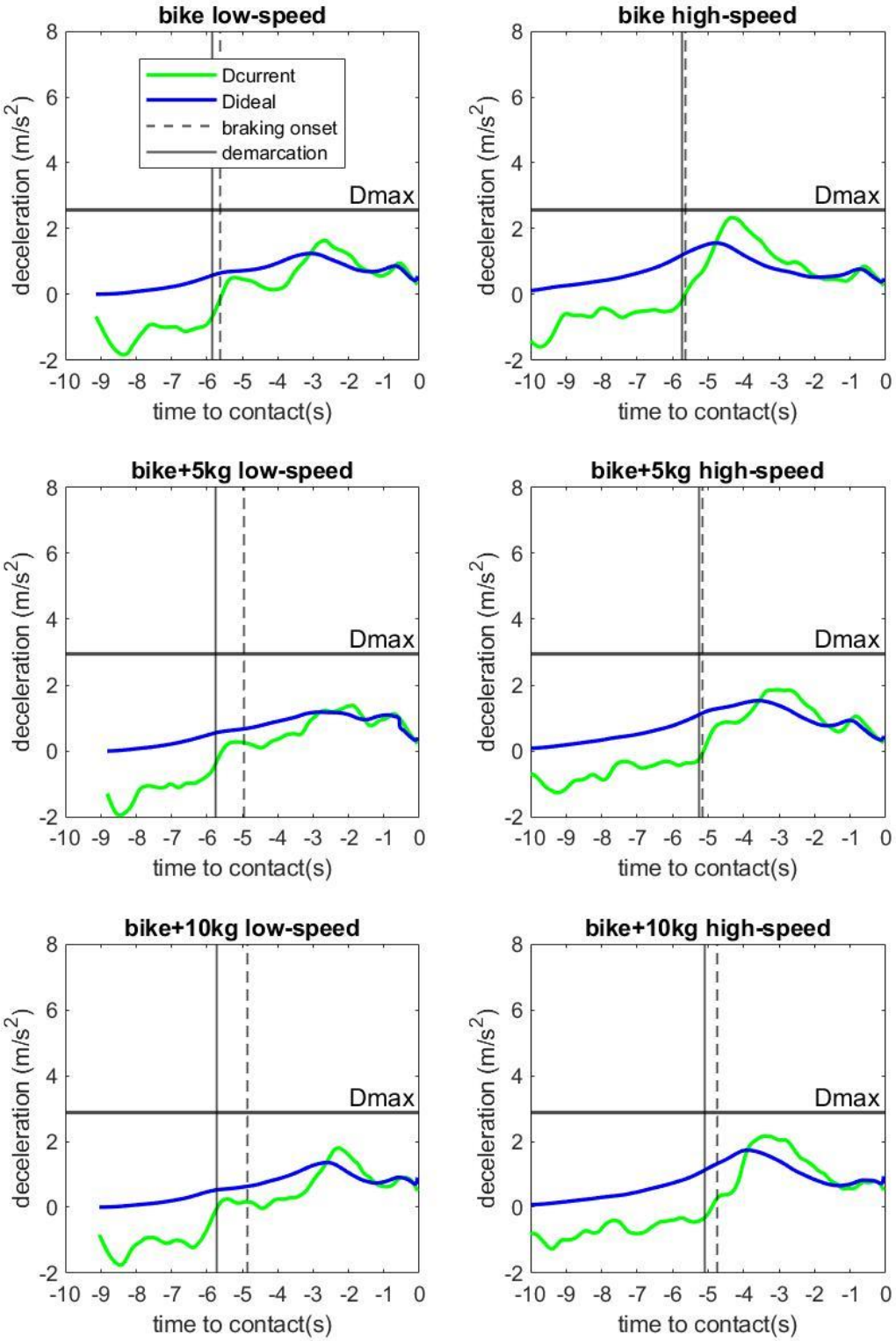

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s2)
time to contact(s)

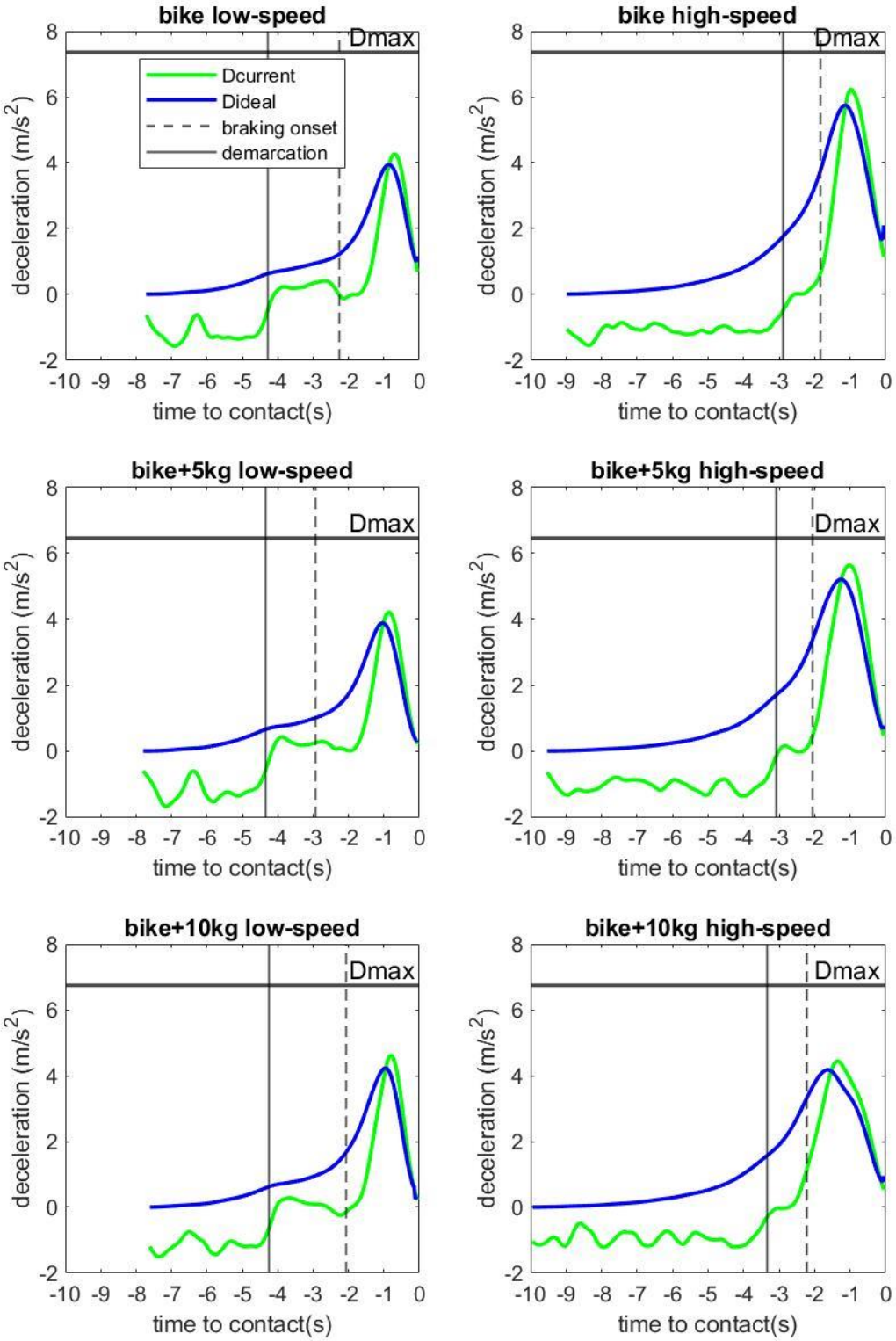

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s^2)
time to contact(s)

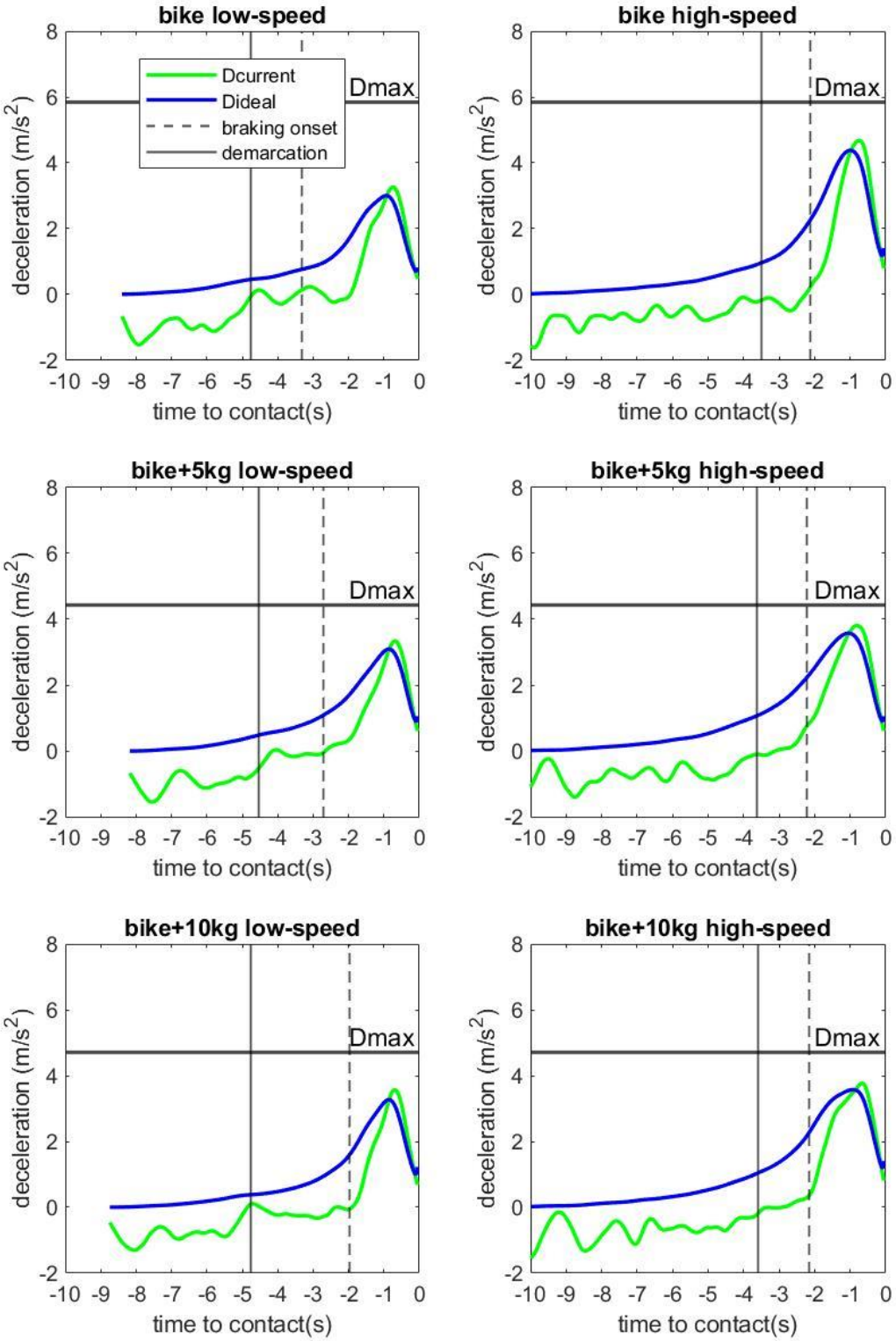

bike low-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s2)
time to contact(s)
bike high-speed
Dmax
deceleration (m/s2)
time to contact(s)
bike+5kg low-speed
Dmax
deceleration (m/s2)
time to contact(s)
bike+5kg high-speed
Dmax
deceleration (m/s2)
time to contact(s)
bike+10kg low-speed
Dmax
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time to contact(s)
bike+10kg high-speed
Dmax
deceleration (m/s2)
time to contact(s)

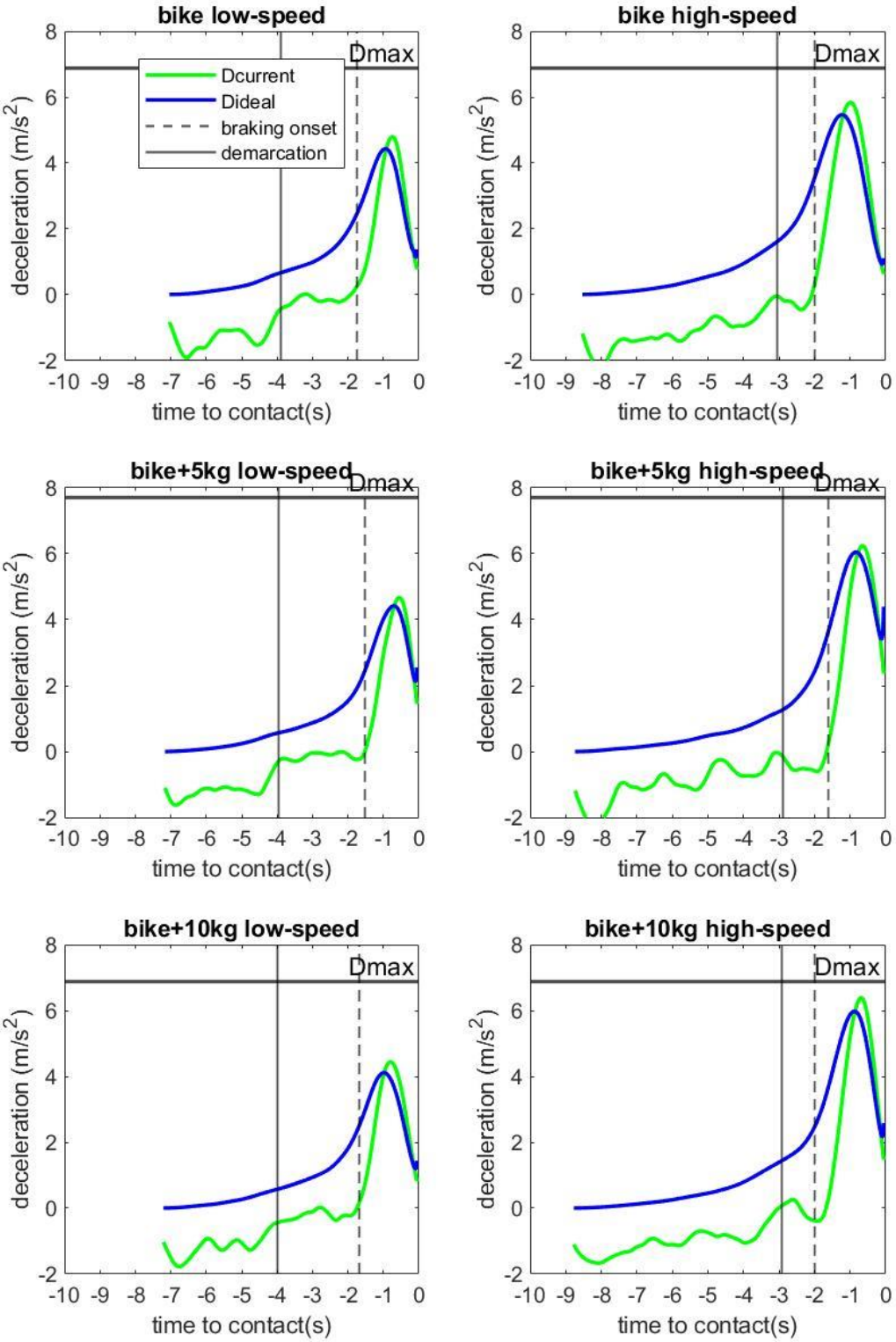

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s^2)
time to contact(s)

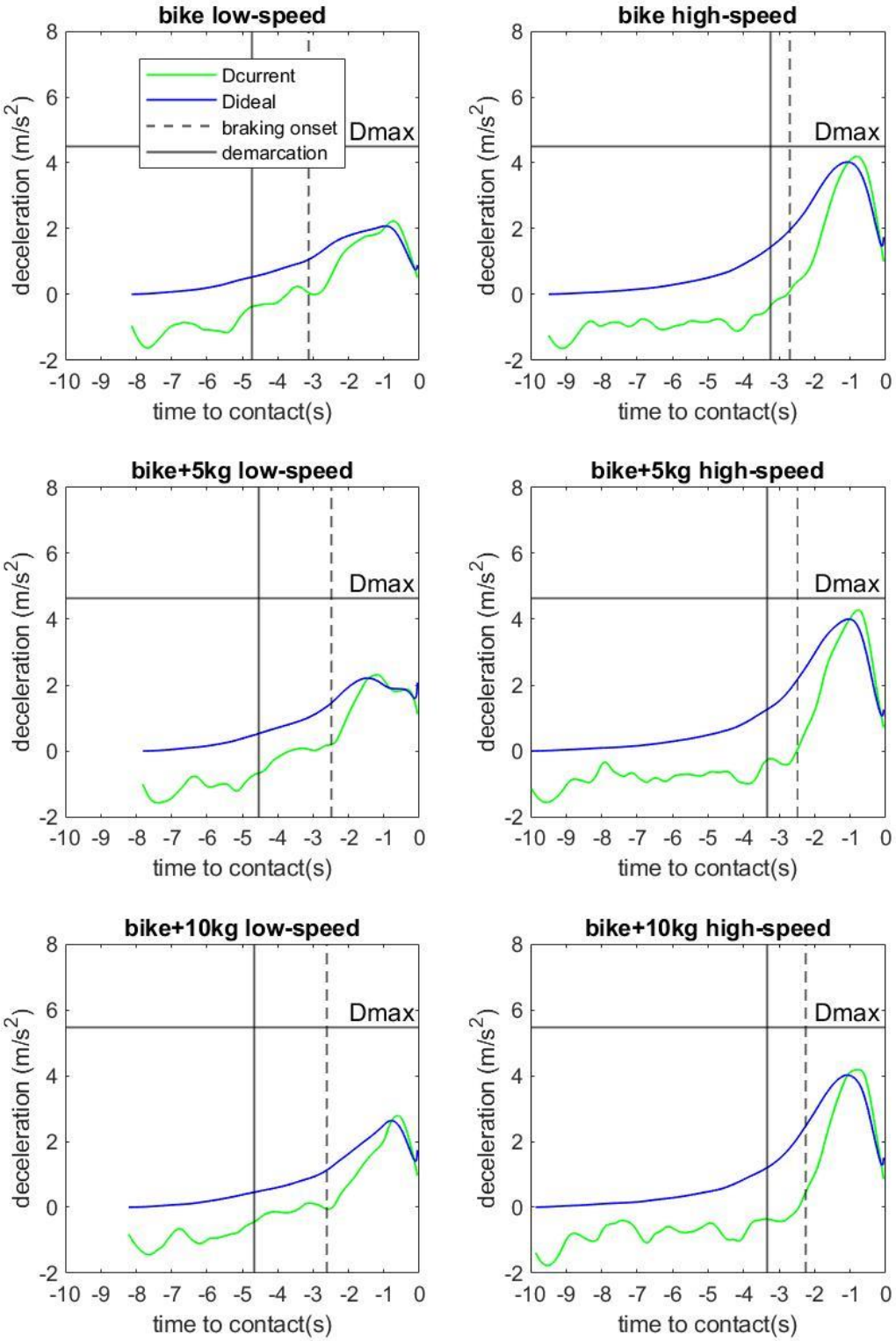

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s^2)
time to contact(s)

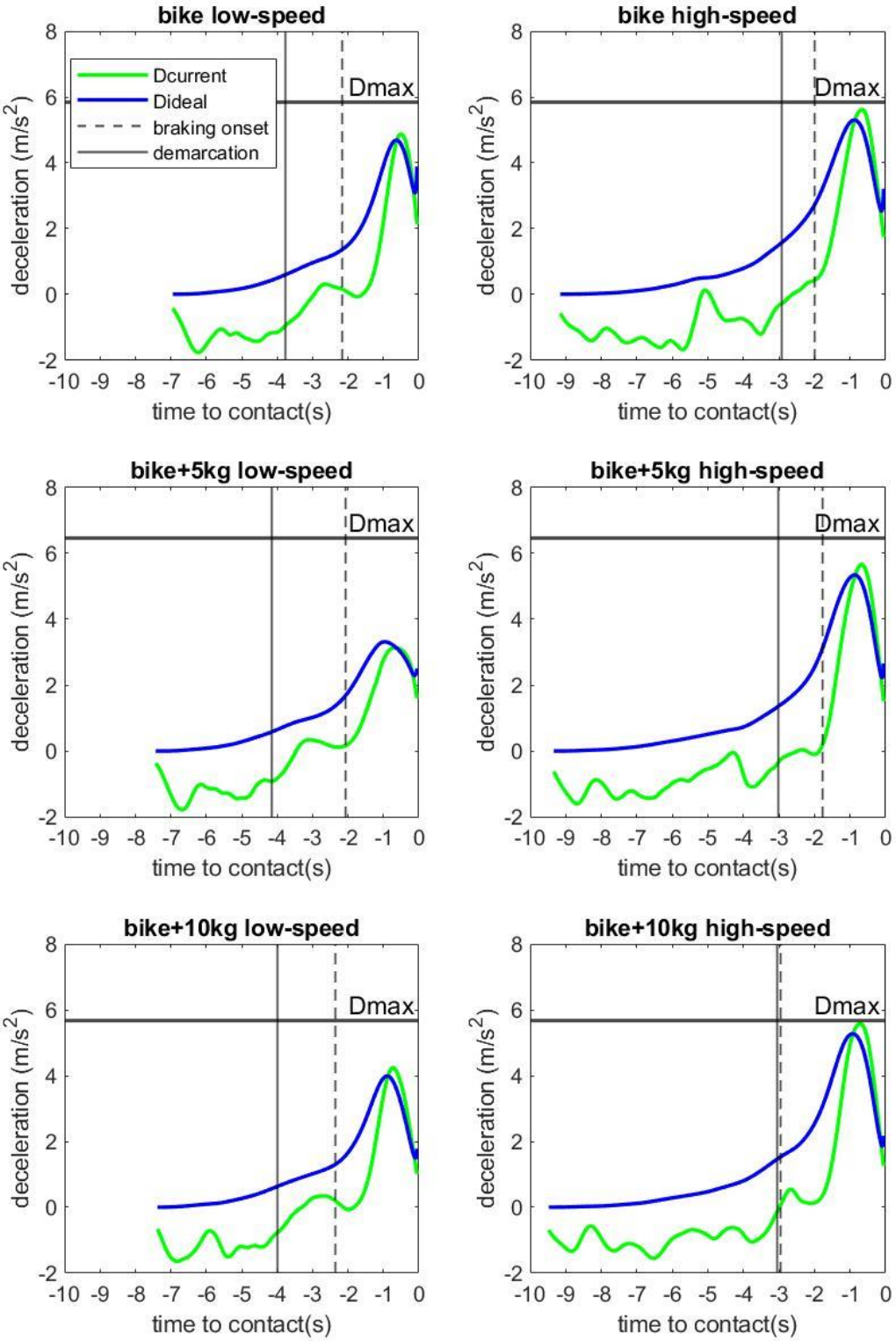

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s2)
time to contact(s)

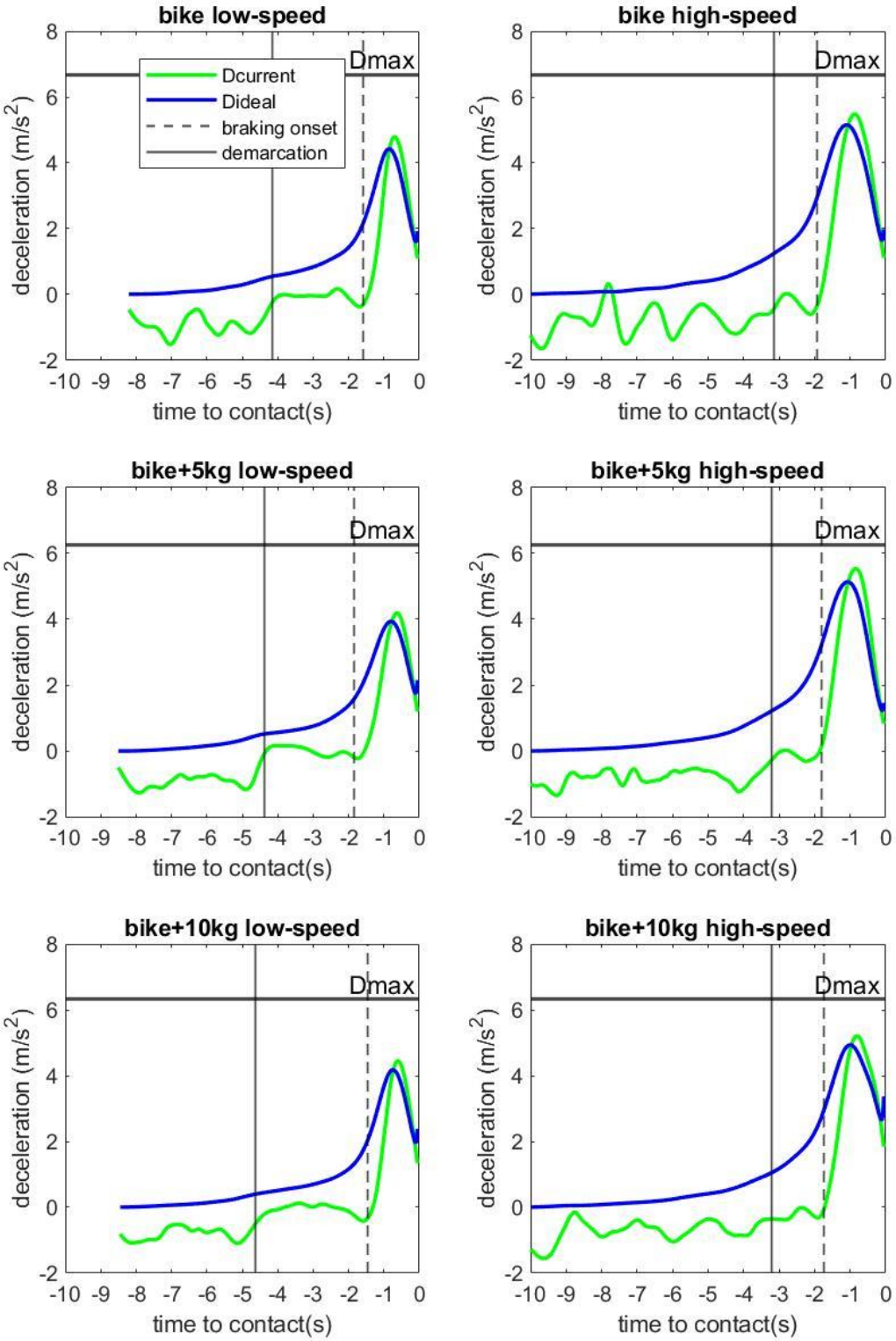

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dmax
Dcurrent
Dideal
braking onset
demarcation
deceleration (m/s^2)
time to contact(s)

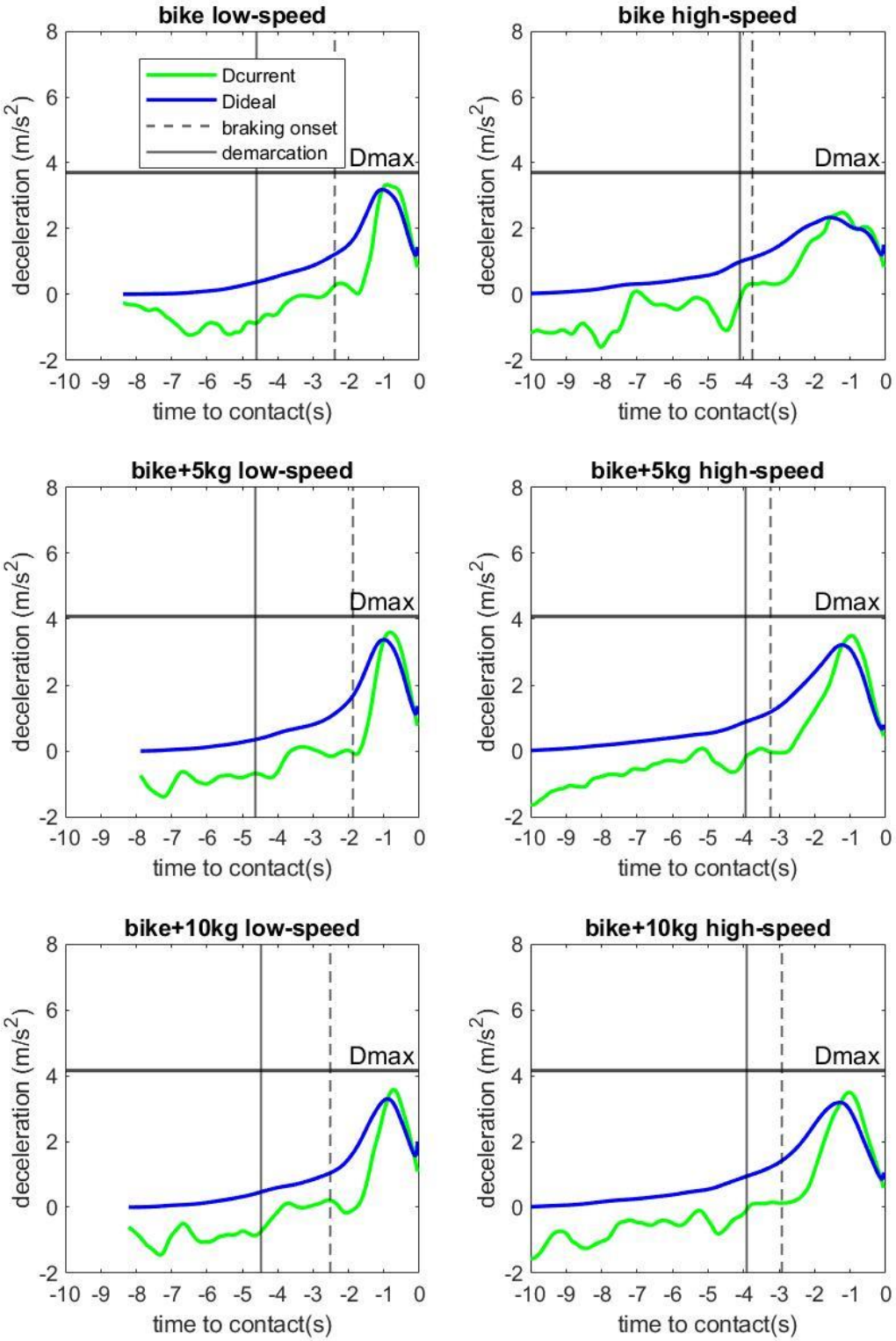

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
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bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s^2)
time to contact(s)

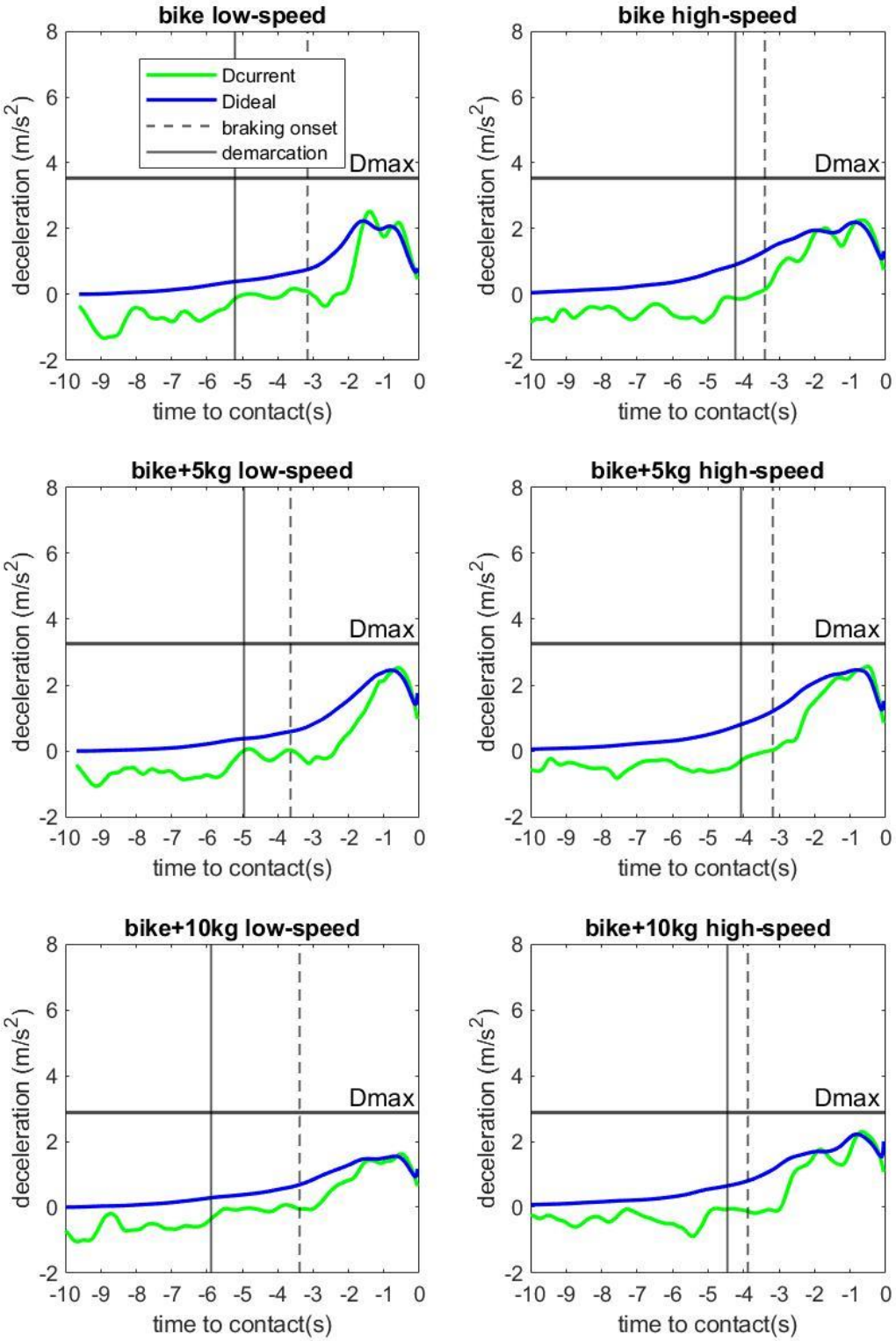

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dmax
Dcurrent
Dideal
braking onset
demarcation
deceleration (m/s^2)
time to contact(s)

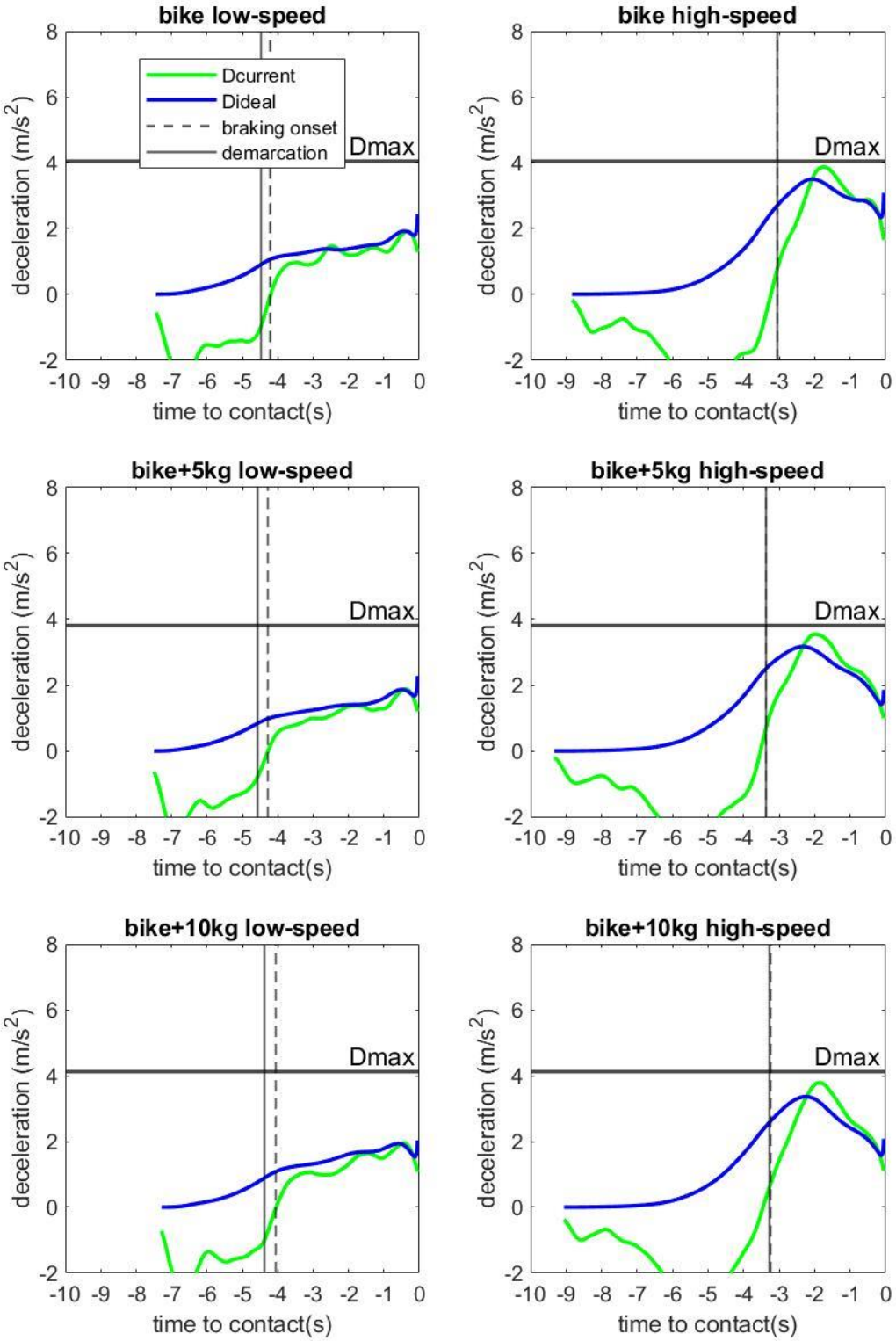

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s^2)
time to contact(s)

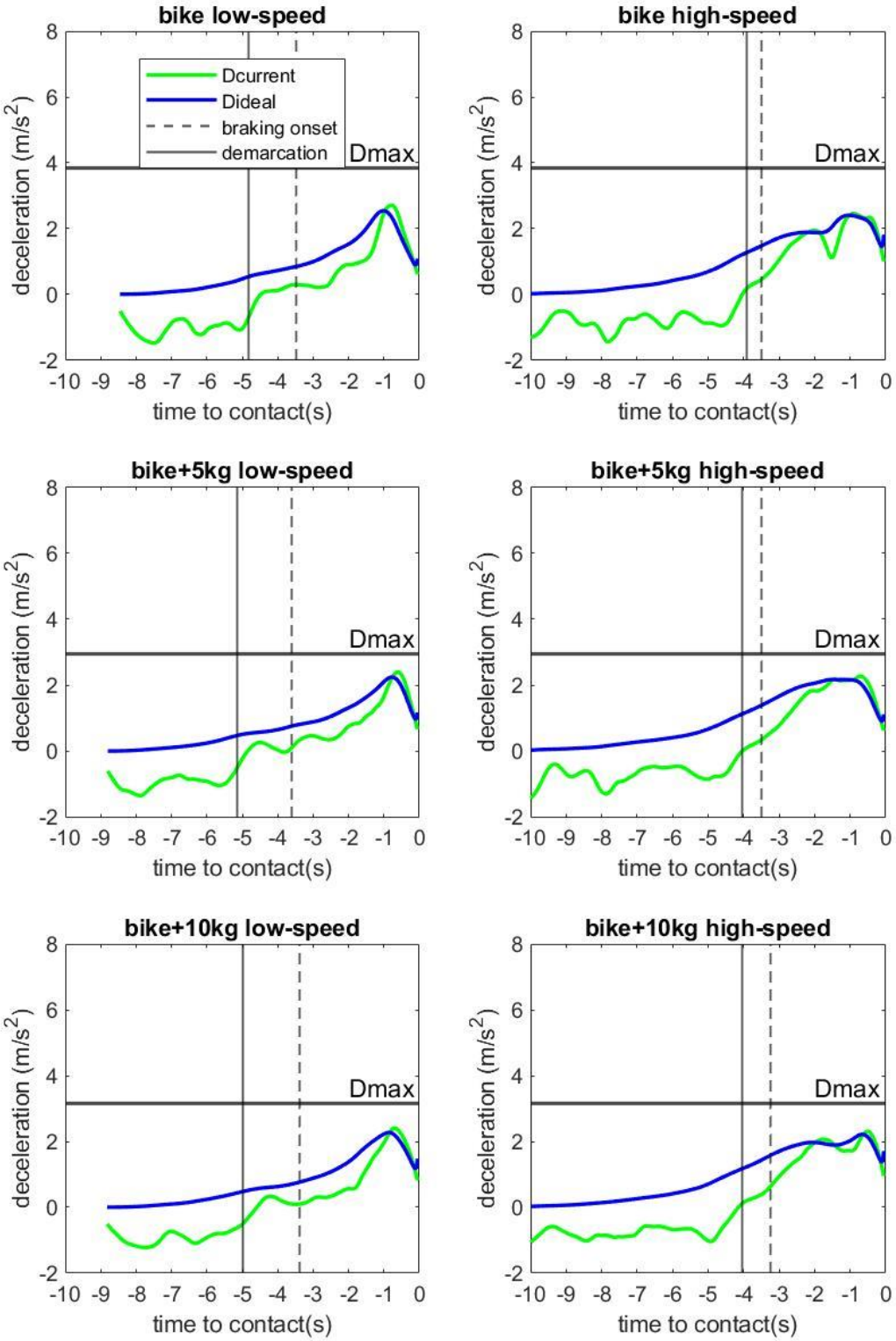

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s^2)
time to contact(s)

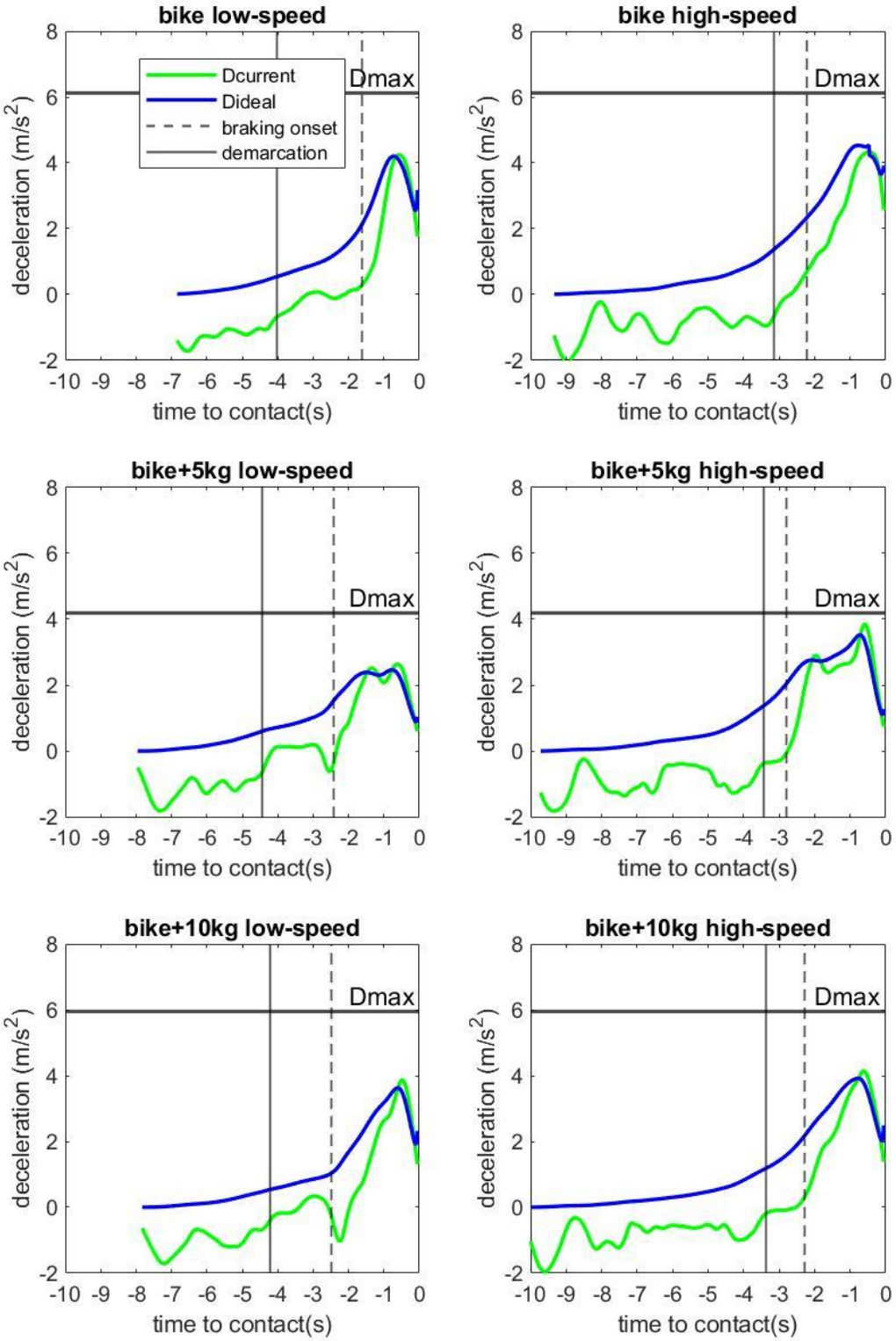

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dmax
Dcurrent
Dideal
braking onset
demarcation
deceleration (m/s^2)
time to contact(s)

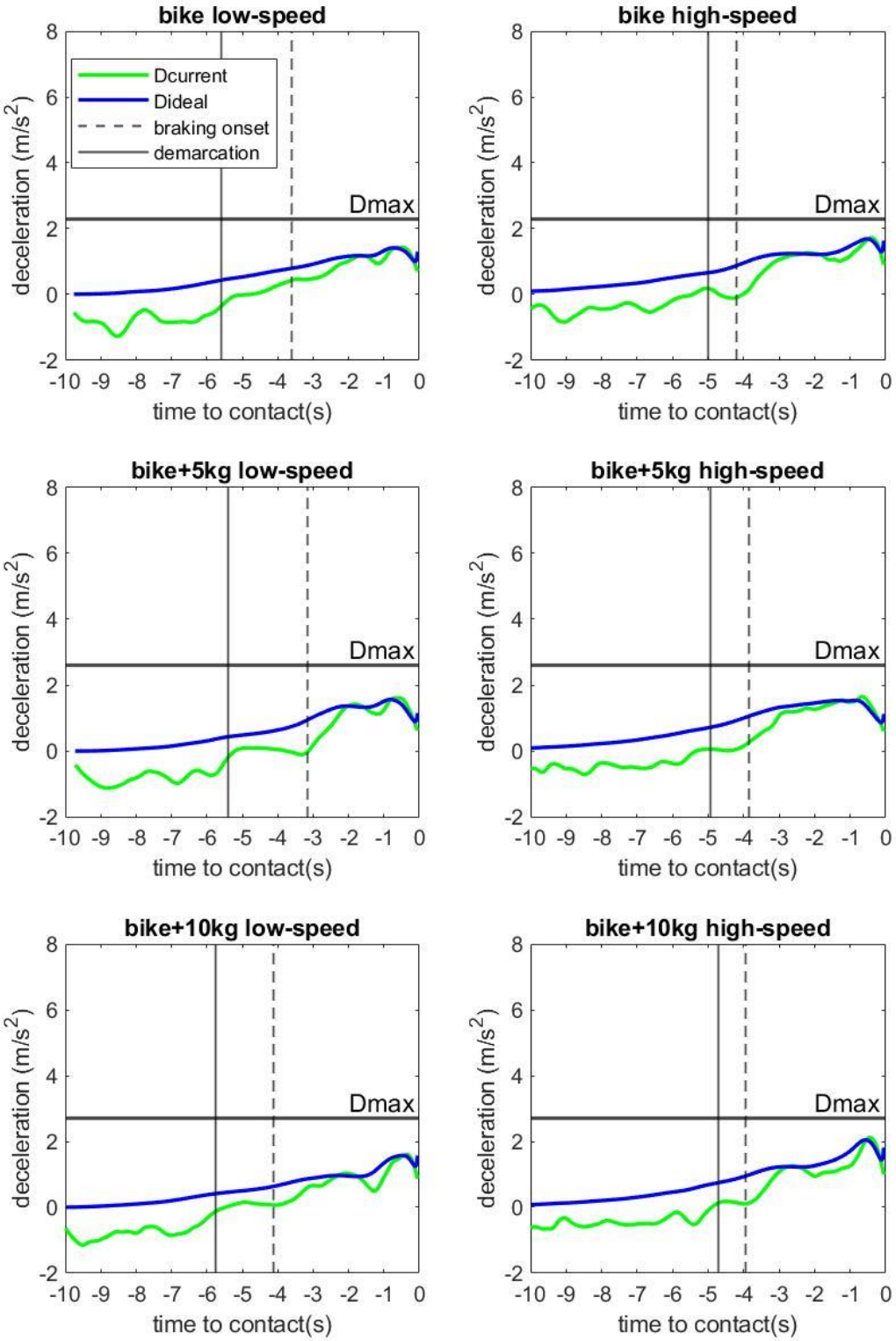

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s^2)
time to contact(s)

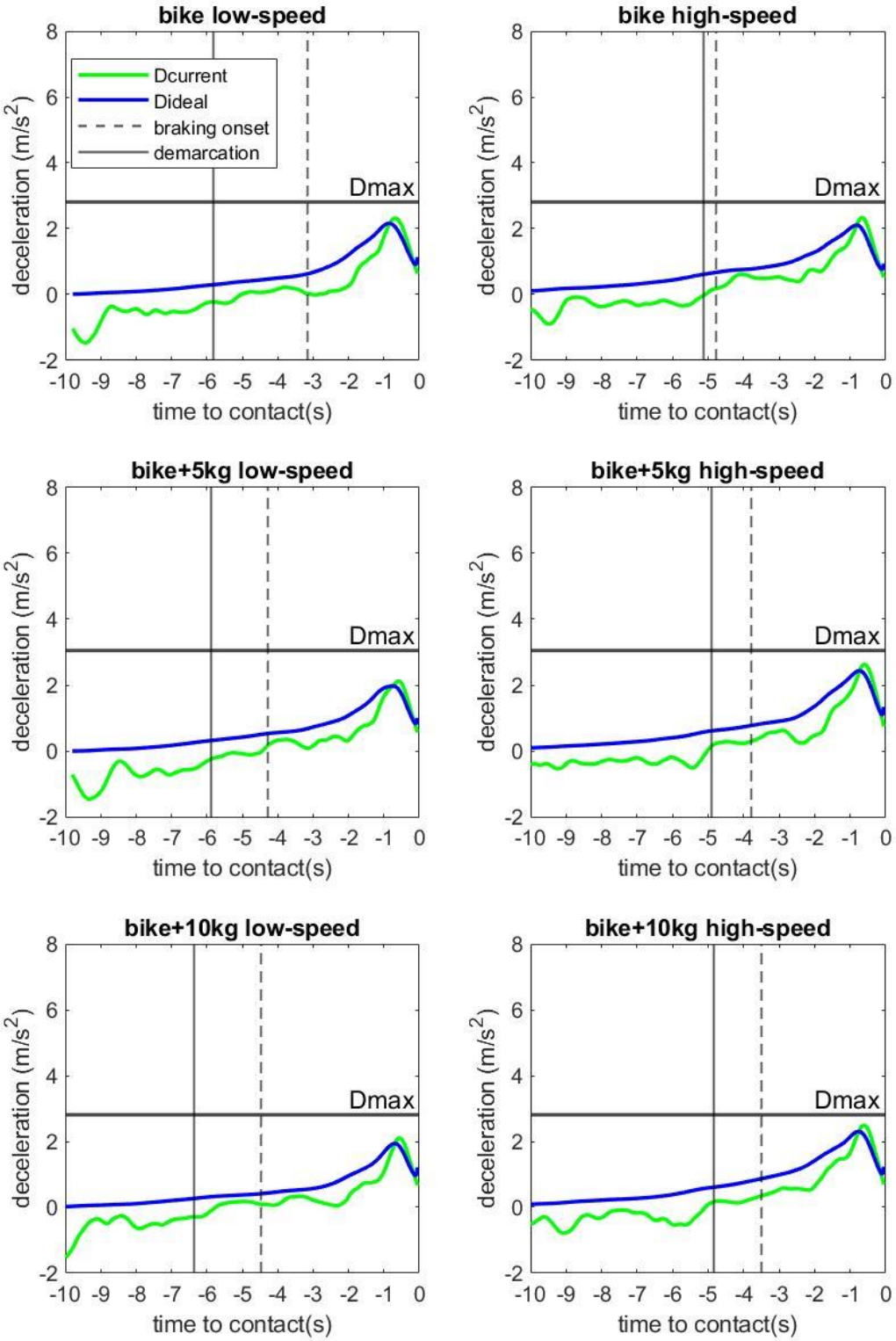

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
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bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s2)
time to contact(s)

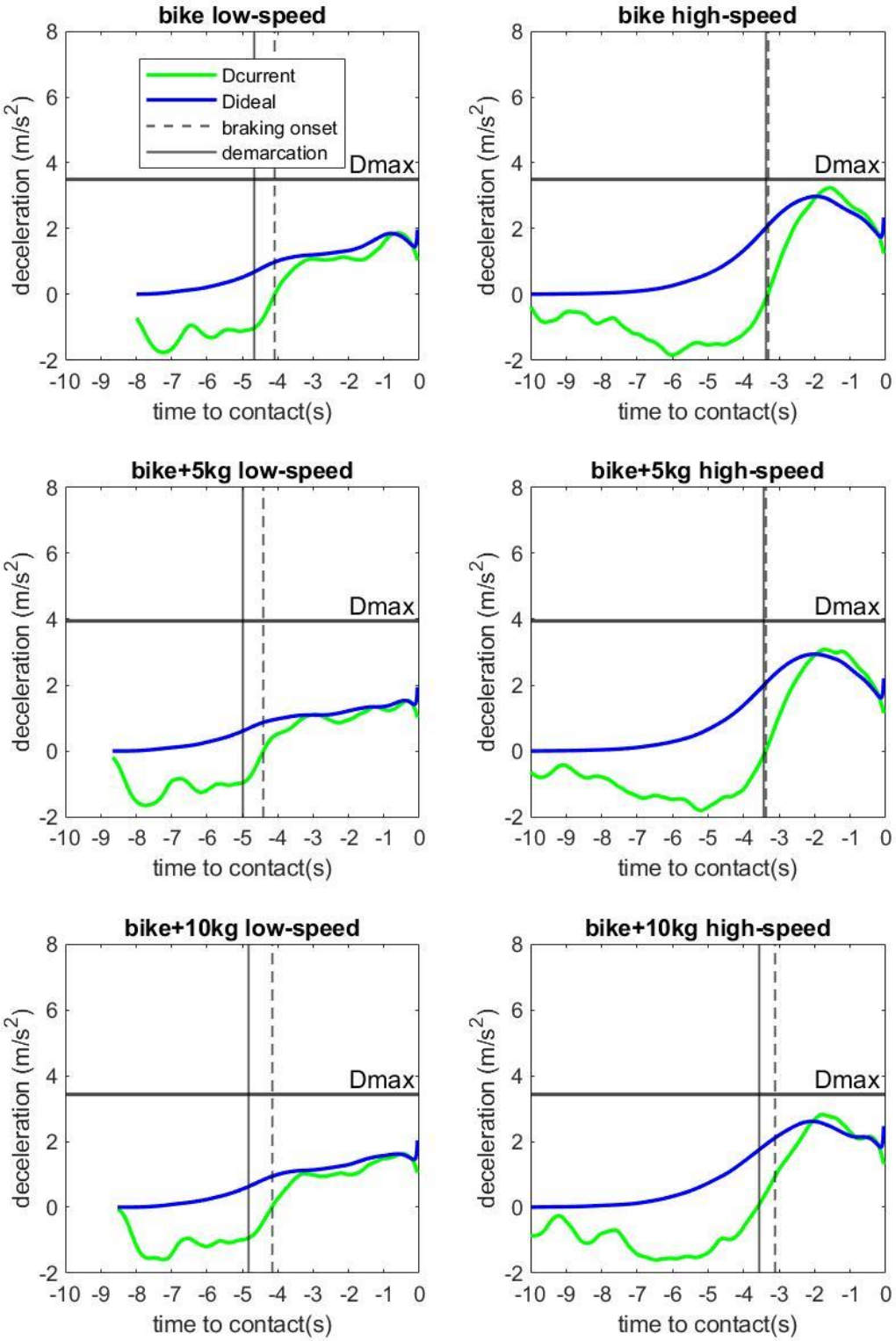

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s2)
time to contact(s)

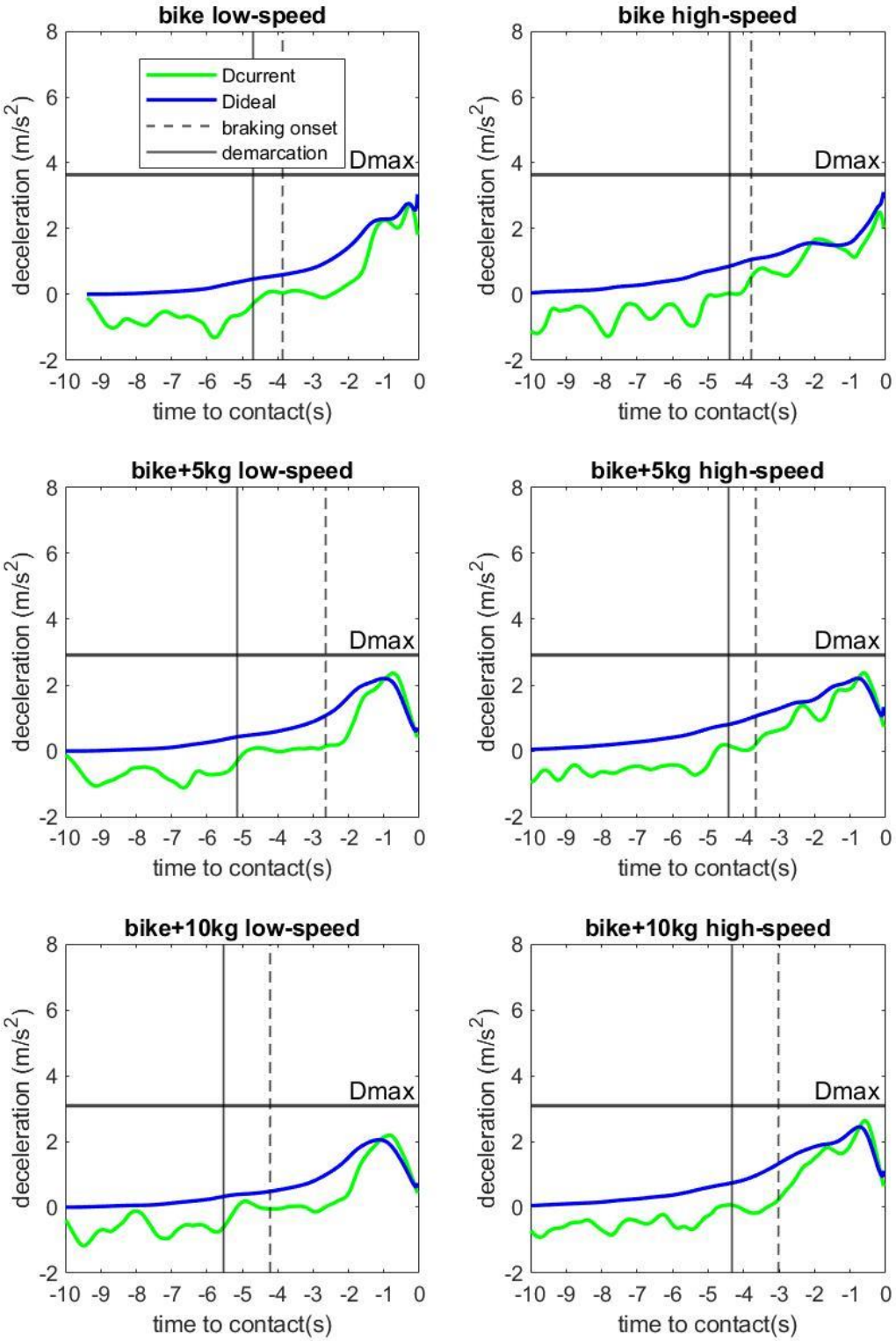

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s2)
time to contact(s)

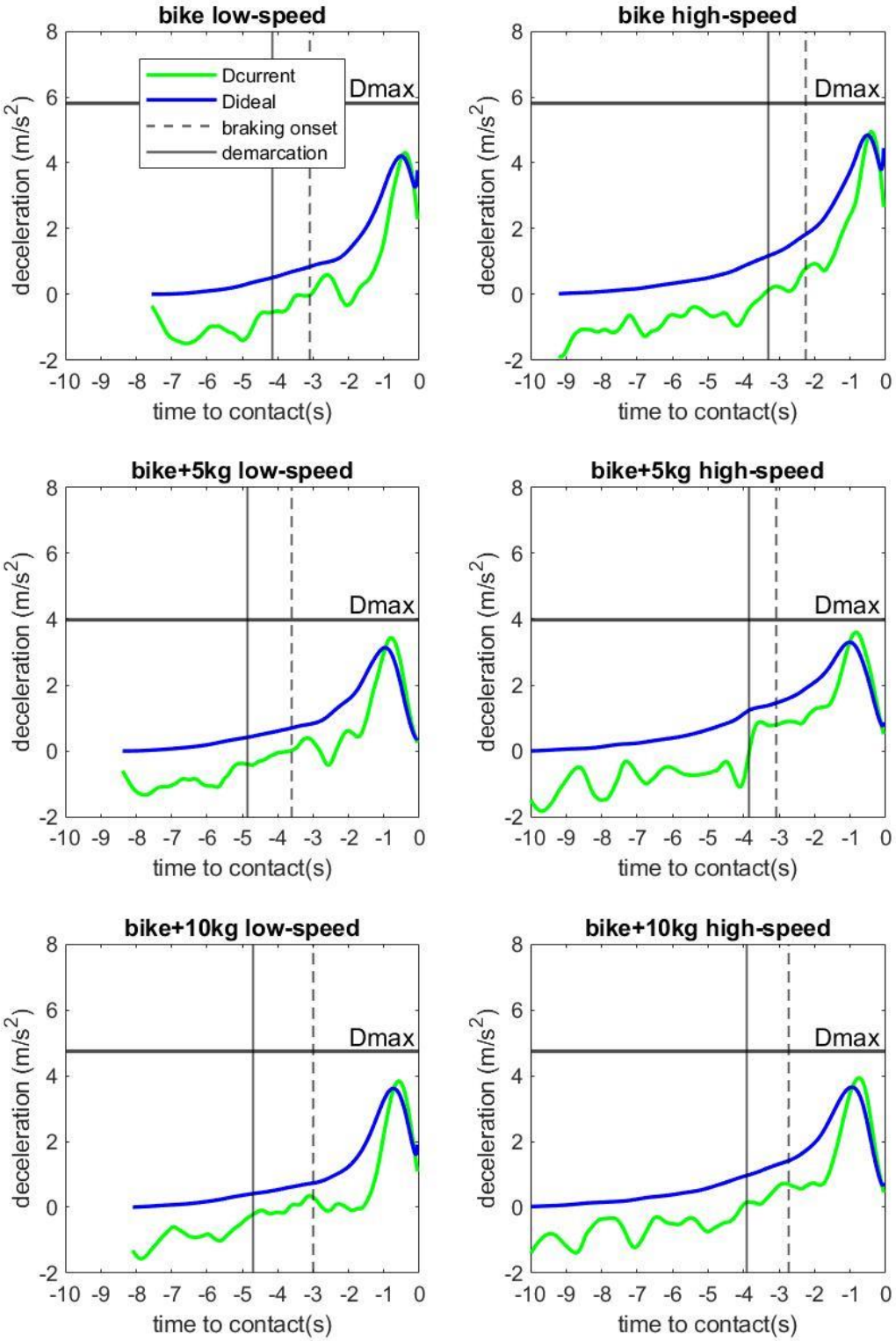

bike low-speed
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bike+5kg low-speed
bike+5kg high-speed
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bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s2)
time to contact(s)

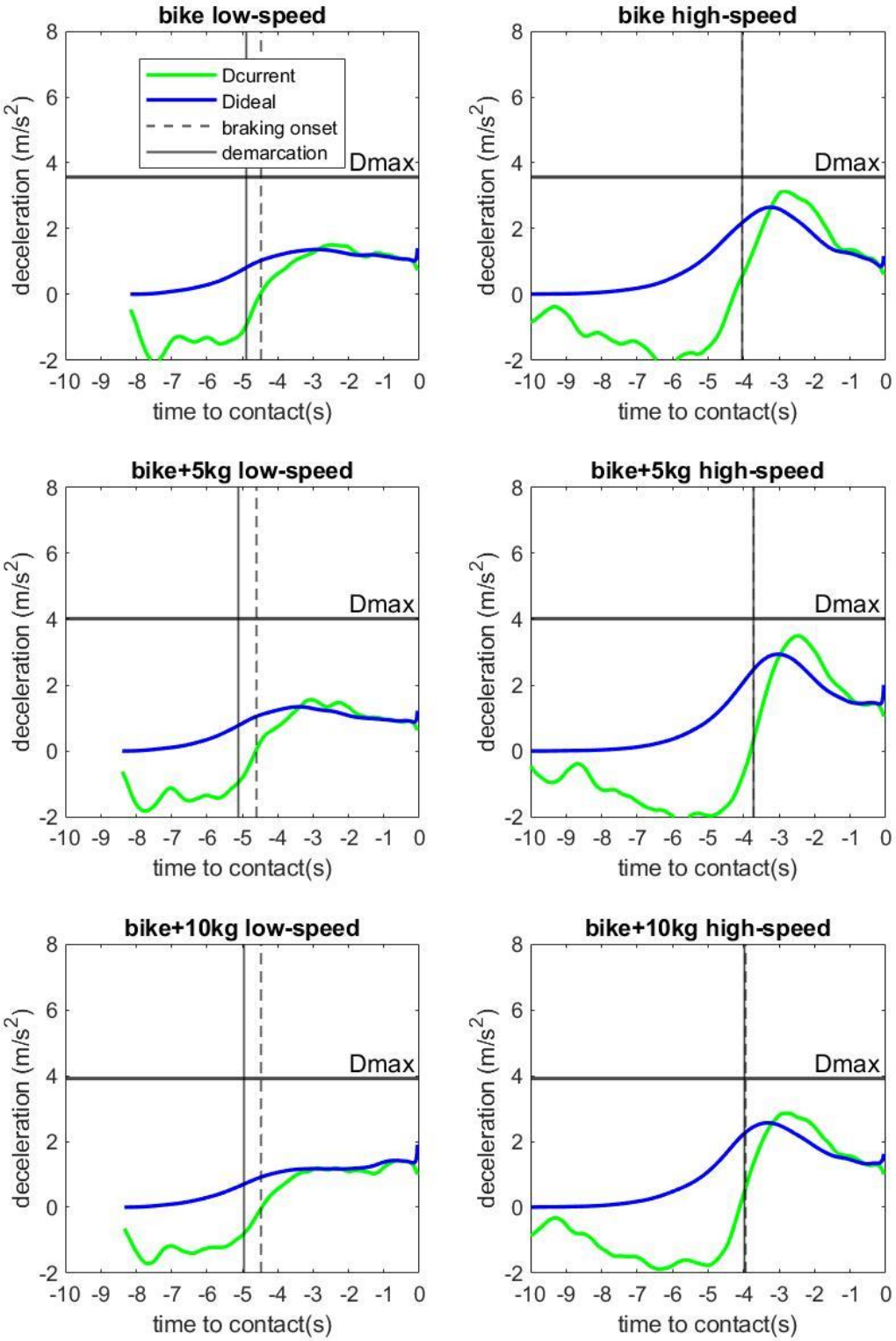

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s2)
time to contact(s)

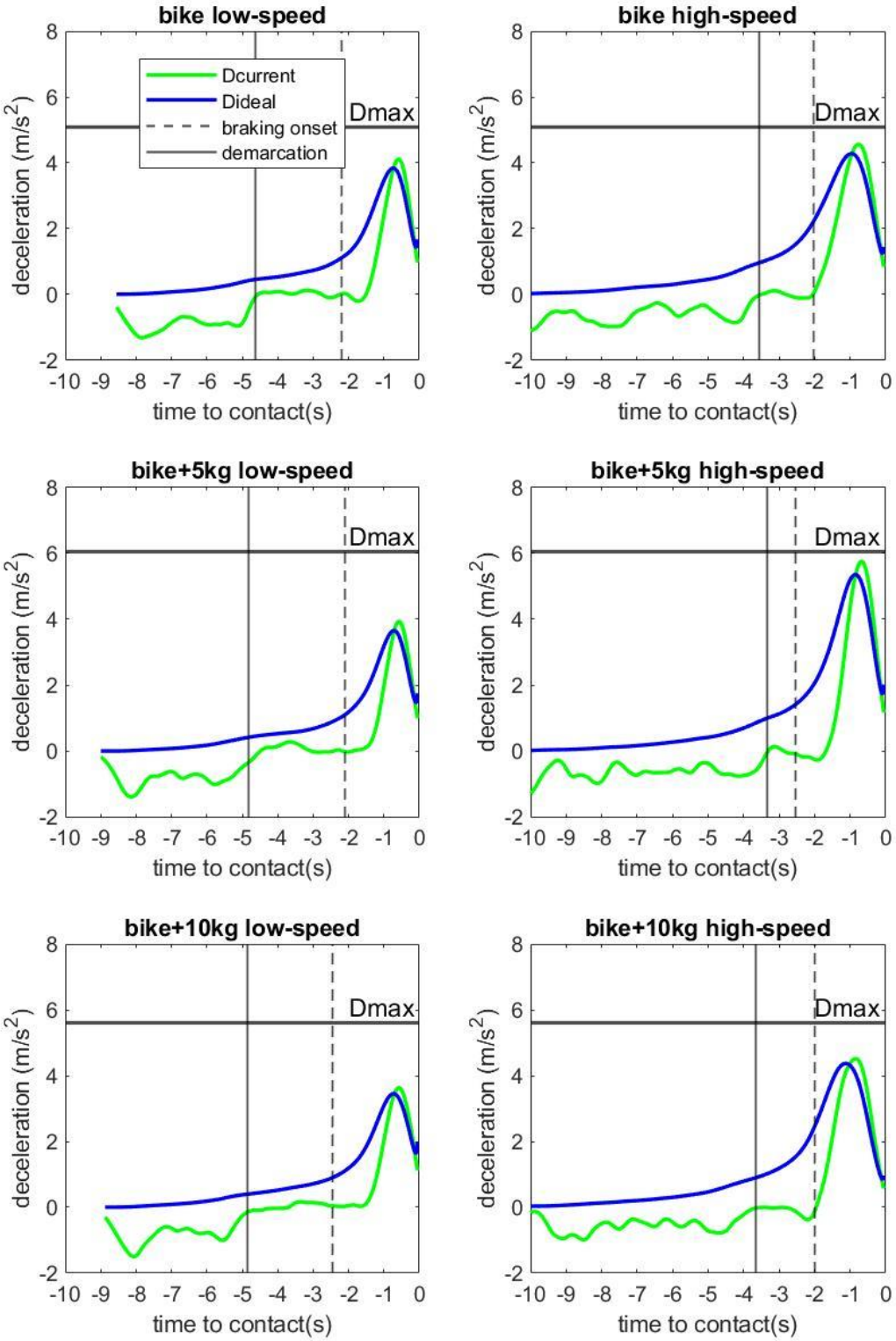

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s2)
time to contact(s)

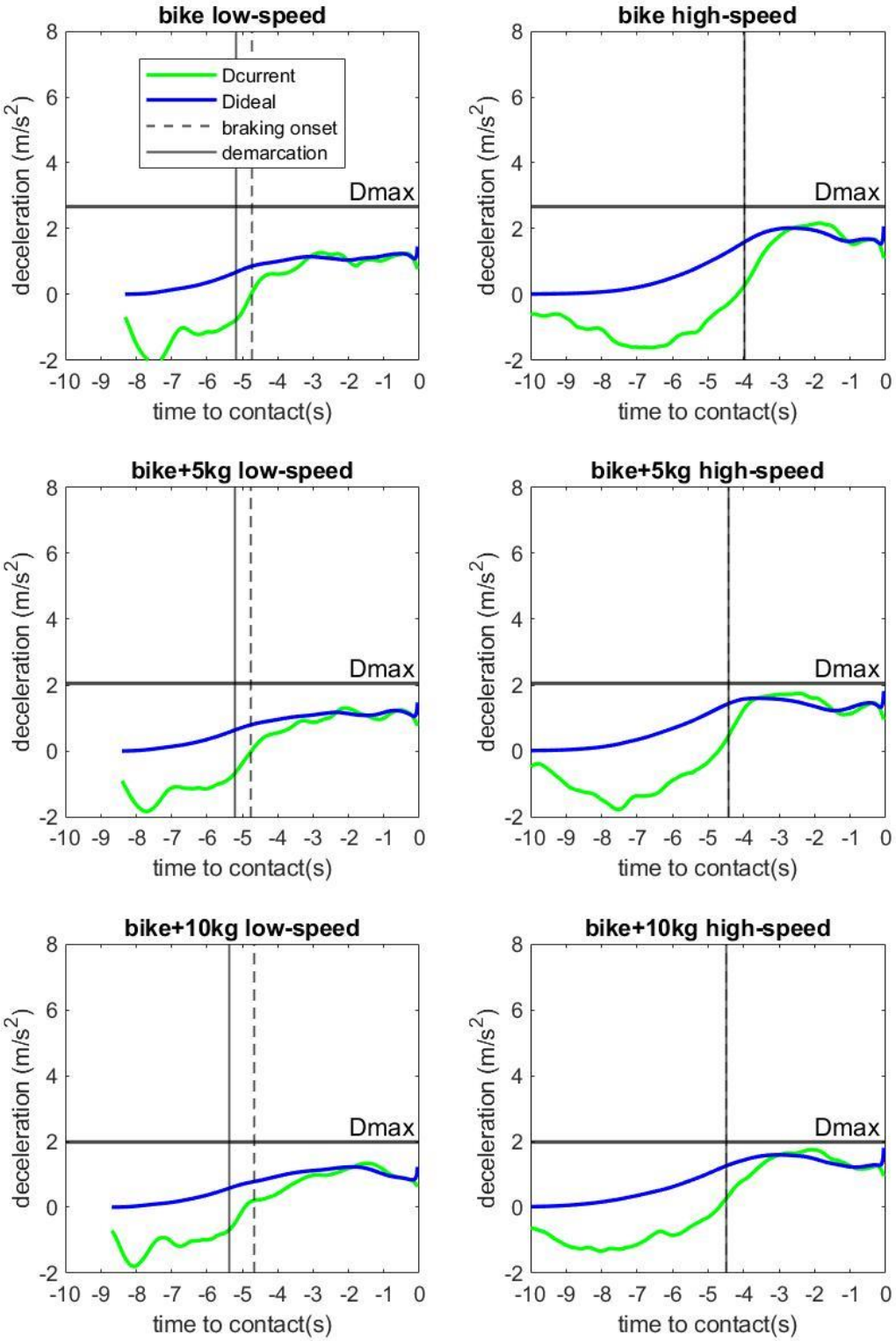

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s^2)
time to contact(s)

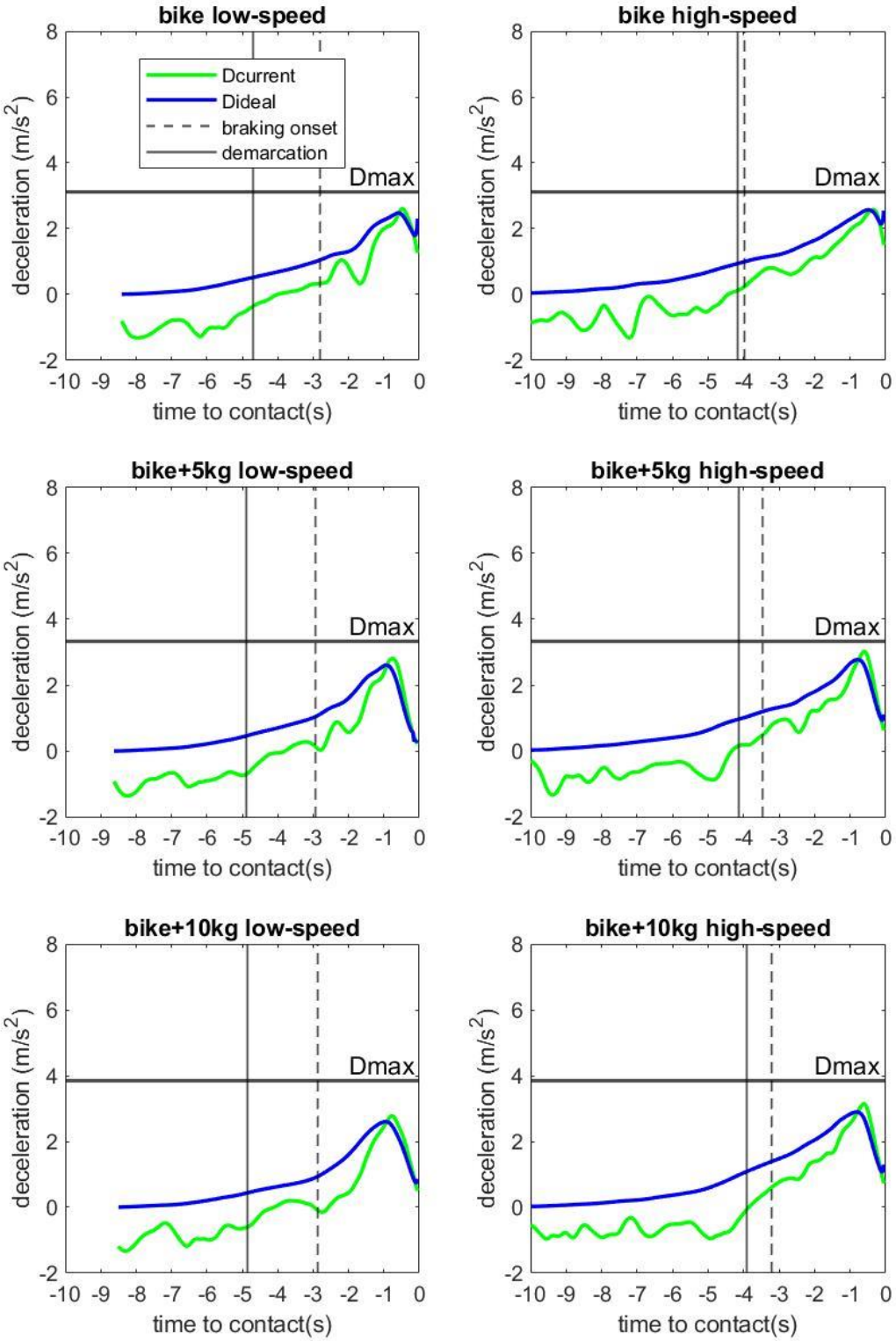

bike low-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s2)
time to contact(s)
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed

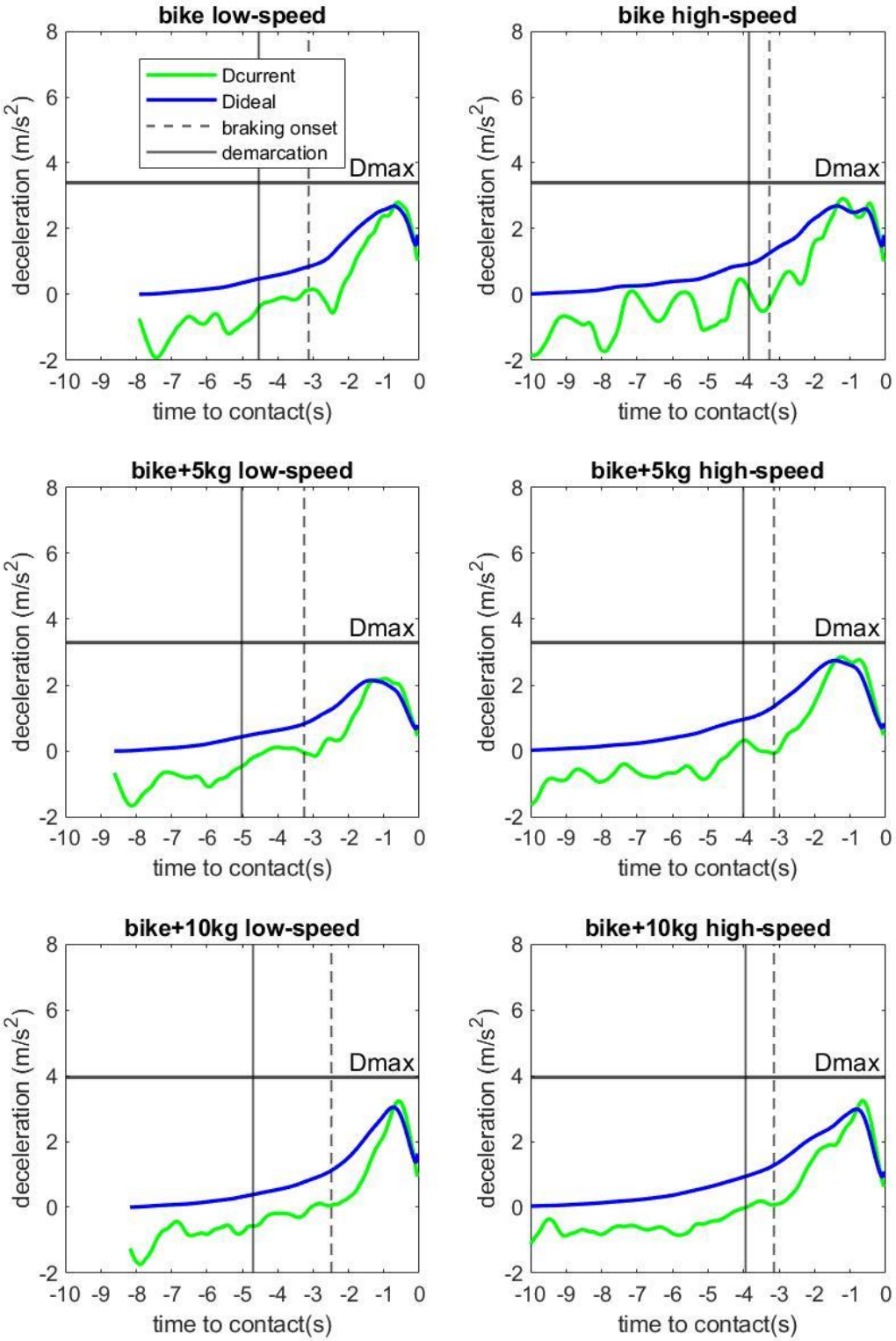

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s^2)
time to contact(s)

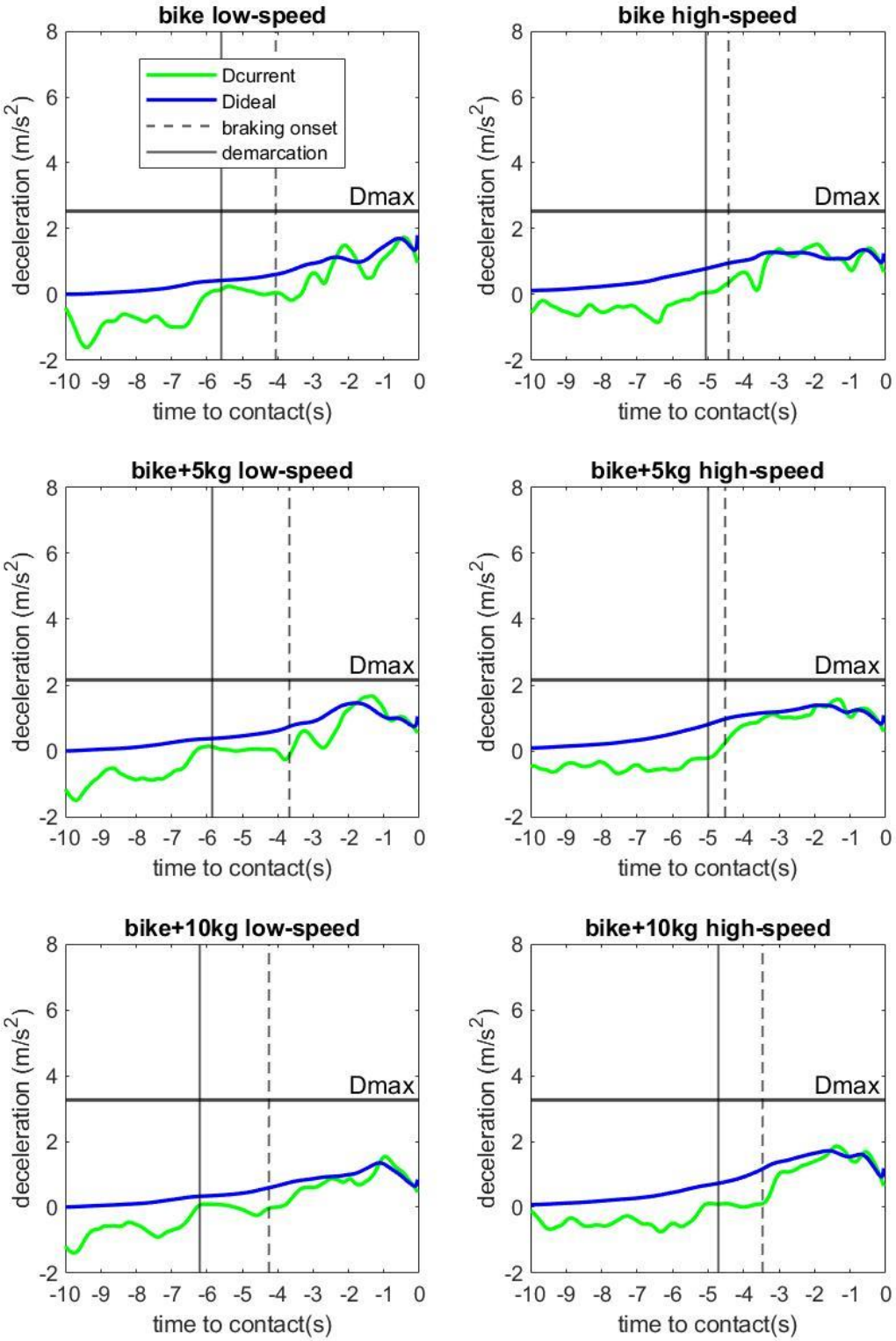

bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s2)
time to contact(s)


bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s2)
time to contact(s)


bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s2)
time to contact(s)


bike low-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s2)
time to contact(s)
bike high-speed
Dmax
deceleration (m/s2)
time to contact(s)
bike+5kg low-speed
Dmax
deceleration (m/s2)
time to contact(s)
bike+5kg high-speed
Dmax
deceleration (m/s2)
time to contact(s)
bike+10kg low-speed
Dmax
deceleration (m/s2)
time to contact(s)
bike+10kg high-speed
Dmax
deceleration (m/s2)
time to contact(s)


bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s2)
time to contact(s)


bike low-speed
bike high-speed
bike+5kg low-speed
bike+5kg high-speed
bike+10kg low-speed
bike+10kg high-speed
Dcurrent
Dideal
braking onset
demarcation
Dmax
deceleration (m/s2)
time to contact(s)

S.3. Chapter 6 experimental setup photos and codes



Figure A1. Top view of the ramp. Image by Google maps: https://www.google.nl/maps/@52.3723787,4.9368801,259m/data=!3m1!1e3?entry=ttu



Figure A2. Side view of the ramp. Image by the digital camera used in the study.

R Script developed by the authors to calculate the dynamic time warping (DTW) and clustering analysis:
https://github.com/Gotargis/supplemmentary_paper_slopes.git

List of Publications

P.1. Publications as first author

Gotardi GC, Van der Kamp J, Navarro M, Savelsbergh GJ, Rodrigues ST. Affordance-based control of braking in cycling: Experience reveals differences in the style of control. Human movement science. 2024 Jun 1;95:103225. DOI: https://doi.org/10.1016/j.humov.2024.103225

Gotardi GC, Barbieri FA, Simão RO, Pereira VA, Baptista AM, Imaizumi LF, Moretto G, Navarro M, Polastri PF, Rodrigues ST. Parkinson's disease affects gaze behaviour and performance of drivers. Ergonomics. 2022 Jan 21:1-0. DOI: https://doi.org/10.1080/00140139.2022.2028901

Gotardi GC, Rodrigues ST, Barbieri FA, Brito MB, Bonfim JV, Polastri PF. Wearing a head-mounted eye tracker may reduce body sway. Neuroscience letters. 2020. Mar 23;722:134799. DOI: https://doi.org/10.1016/j.neulet.2020.134799

Gotardi GC, Kuga GK, Simão RO, Brito MB, Paschoalino GP, Silva GA, Barbieri FA, Polastri PF, Schor P, Navarro M, Rodrigues ST. Combining experiences of race gaming and natural driving affects gaze location strategy in simulated context. Ergonomics. 2019. Nov 2;62(11):1392-9. DOI: https://doi.org/10.1080/00140139.2019.1652770

Gotardi GC, Polastri PF, Schor P, Navarro M, Oudejans RRD, van der Kamp J, Savelsbergh GJP, Rodrigues ST. Adverse effects of anxiety on attentional control differ as a function of experience: a simulated driving study. Applied Ergonomics. 2019. 74:41-47. DOI: https://doi.org/10.1016/j.apergo.2018.08.009

P.2. Publications as co-author

Brito MB, **Gotardi GC**, Rodrigues ST, Jacomassi DG, Bonnet CT, Polastri PF. Functional relation between postural sway and saccadic eye movements is strong and not altered by moving visual environment and concomitant memory task. Adaptive Behavior. 2023. 0(0). DOI: https://doi.org/10.1177/10597123231208034

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