Designing the Communication with Automated Vehicles: The Case of Elderly Pedestrians

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To communicate perception of and intent to other road users, implicit and explicit forms of communication for automated vehicles (AVs) are currently under research and development. Despite being a relevant group for road safety, the requirements of elderly pedestrians are not sufficiently reflected in current communication concepts. Age-related impairments of sensory, cognitive and motor abilities of elderly pedestrians are presented and their relevance for design criteria of implicit and explicit forms of communication for AVs derived. The specification of design criteria presented in this paper allows further research to examine the design of implicit and explicit communication for AVs with elderly pedestrians.

Additional Key Words and Phrases: elderly pedestrians, automated vehicles, human-machine interaction, communication, age-related impairments

1 BACKGROUND

As the proportion of elderly people (age 65 and older) in western countries is increasing [38], there is a growing interest regarding the mobility needs of this demographic group [57]. Walking as a pedestrian is one common mode of transportation for elderly people [33]. Among all road users, pedestrians represent an especially vulnerable group in road traffic [37]. While elderly people represent 20% of the EU population they account for 47% of all pedestrians' deaths in the EU [3], making them a critical age group regarding road safety. Aging brings greater difficulties in crossing the road especially in complex traffic scenarios such as two-way roads [17, 19, 40]. Difficulties in road-crossing behavior of the elderly have been attributed to age-related declines in sensory, cognitive and/or motor abilities [16, 41].

Today, road crossings by pedestrians can be accompanied by the interaction with human drivers, which is characterized by an exchange of implicit (e.g. deceleration, gait) and explicit (e.g. hand gestures) signals [14, 55]. In doing so road users communicate perception of and intention to other road users in their environment [35]. With automated vehicles (AVs) in the urban transportation system new challenges arise [5], one of them being the communication of AVs with other road users [42, 55]. While research has focused on designing implicit and explicit forms of communication for AVs [e.g. 1, 48], elderly people have only seldom been the user group of design and evaluation [e.g. 26, 34, 39, 44].

This paper highlights the gap between current design concepts of implicit and explicit communication for AVs and the requirements of elderly pedestrians. Therefore, age-related impairments of elderly pedestrians are described (section 2) and their relevance for current developments in implicit and explicit forms of communication for AVs derived (section 3). This (brief) review shall inform further research examining the design of communication between elderly people and AVs by deriving research gaps in literature (section 4).

2 AGE-RELATED IMPAIREMENTS OF ELDERLY PEDESTRIANS

To ensure safe road-crossing decisions, pedestrians must "share their attention, select the most appropriate information and inhibit the information that is non relevant" [16, p. 136], followed by the execution of an action to cross the road.

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Thus, participation as a pedestrian in road traffic requires the integration of sensory, cognitive and motor abilities [16, 60].

2.1 Sensory abilities

The visual and auditory perception are of great relevance in road-crossing decisions of pedestrians [43]. Known age-related deteriorations of visual perception are the decline of central and dynamic visual acuity [8, 24] with the latter being of particular relevance for motion perception [54]. Moreover, the aging eyes' impaired accommodation hinders their ability to adapt between focusing near and far [8]. While contrast sensitivity as well as color discrimination are reduced, glare sensitivity is increased [8, 24]. Since the interaction of the foveal and peripheral visual field forms the basis for visual orientation, age-related narrowing of the "Useful Field of View" must be considered as well [52]. With regard to auditory perception, the elderly person's ability to perceive and locate acoustic signals and to filter out unwanted sounds is hampered [18, 51].

Age-related declines in sensory abilities have been shown to impact road-crossing decisions of pedestrians [15, 16]. The visual perception is necessary to perceive objects at a distance, to recognize signs, signals and other road users and to correctly estimate speeds. Because of their limited sensory abilities, elderly people have difficulties in estimating the time-of-arrival (TTA) of approaching objects and cars [4, 50], potentially leading to dangerous crossing decisions.

2.2 Cognitive abilities

Cognitive abilities refer to skills such as attention, information processing and the ability to reflect and represent memory content [47]. Elderly people need more time to assess a stimulus' contextual relevance and are easier and longer distracted by irrelevant stimuli due to impaired inhibition [22, 25]. Having difficulty in flexibly distributing attention between two tasks, maintaining a prioritized focus and switching between them, situations requiring divided attention pose problems for the elderly [23, 53]. Combined with the age-related reduction of a person's limited working memory [7] and the reduced speed of information processing [49], the search for target stimuli in complex environments under time constraints is impeded [59].

Due to age-related declines in cognitive abilities, elderly pedestrians are more likely to have difficulties in the decision making process when crossing a road, especially under time pressure [60]. Related gap-selection issues of elderly pedestrians [32, 41] are also attributed to decreasing cognitive abilities that pedestrians need to focus on relevant information and to make timely, correct decisions [16].

2.3 Motor abilities

Changes in the bone, joint, ligament and muscle apparatus have effects on mobility, speed of movement, balance, coordination and strength [10]. A decrease of muscle strength of up to 30-40% over the lifespan [46] and a decrease in mobility of about 3-5% per decade [56] reduce the elderly person's ability, power, controllability and precision of movement execution [46]. With increasing age, sensomotoric tasks like everyday movement patterns require more conscious control and cognitive resources, limiting the capacity to perform multiple activities simultaneously [31].

Elderly pedestrians display slower walking speeds while crossing a road [32, 40] whereby walking time is a relevant factor to predict the safety of pedestrian crossing behavior [27]. Difficulties to adapt their walking speed to prevailing traffic conditions further explain gap-selection problems of the elderly [15, 16].

3 DESIGN CONSIDERATIONS FOR THE COMMUNICATION BETWEEN AUTOMATED VEHICLES AND ELDERLY PEDESTRIANS

While research on age-related impairments and their influence on the behavior of elderly pedestrians exists, little research has been done regarding the communication and interaction between AVs and elderly pedestrians. Nevertheless, initial studies have shown that light signals on AVs (light bar on the rooftop) were assessed more positively by elderly pedestrians compared to younger pedestrians (aged 21-30 years) in terms of usefulness and satisfaction [26]. Another study identified the preference of elderly people for multimodal designs (combination of visual and auditory signals) of external Human-Machine Interfaces (eHMIs, e.g. light signals or displays on AVs) but could not find any difference in reported user experience (using the UEQ [29]) between younger (20-30 years old) and elderly pedestrians [39]. Furthermore, a video analysis revealed differences in road user behavior of older people when interacting with an AV, with older pedestrians (aged 55 years and above) stopping more often to give priority to the AV [34]. This result was supported by a simulation experiment in which older pedestrians (aged 40-69 years) were more hesitant about interacting with an AV when crossing a road [44].

While these studies show that there are age-related differences both in subjective assessment as well as behavior when interacting with AVs, none of the above-mentioned research explicitly considered age-related impairments of pedestrians in the design of implicit and explicit forms of communication for AVs. Table 1 compiles age-related impairments and resulting difficulties of elderly pedestrians and matches them with the most relevant design criteria of current developments for the communication design of AVs. Research on older drivers served as a basis to assign design criteria to age-related impairments of pedestrians [e.g. 11]. Further, the relevance of age-related impairments, resulting difficulties of elderly pedestrians and significance of design criteria were discussed in two structured feedbacks during the preparation of this position paper.

Table 1. Age-related impairments of elderly pedestrians and their relevance for designing pedestrian-AV-communication

Age-related impairments	Difficulties of elderly pedestrians	Most relevant design criteria
Sensory abilities		
Central acuity	Object perception, sign and signal recognition	Modality, coding, position
Dynamic acuity	Motion perception, TTA and speed estimation	
Accommodation	Change of focus between near and far objects	
Contrast sensitivity	Distinguish between objects and backgrounds	
Color discrimination	Distinguish between colors of signals	
Glare sensitivity	Loss of central acuity in bright light	
Hearing	Hearing loss, locating of acoutic signals	
Cognitive abilities		
Inhibition	Suppression of irrelevant information	Content, coding, perspective, timing
Selective attention	Concentration on a certain stimuli in the environment	
Divided attention	Attend different stimuli at the same time	
Working memory	Amount of available cognitive resources to store information	
Speed of information processing	Making timely decisions	
Decision making under time pressure	Making correct decisions (e.g. gap-selection)	
Motor abilities		
Movement execution	Speed of walking and head rotation	Content, timing, position

Relevant design criteria determining the communication between AVs and pedestrians are the content road users are exchanging [6, 21] and the timing of the communication [1, 12], e.g. the starting point of deceleration to convey a signal [1]. Furthermore, explicit forms of communication (via eHMIs) include the criteria of modality [9], perspective (e.g. ego- vs. allocentric) [6], coding of information (e.g. form, size, color, frequency and amplitude) [2, 6, 13, 30, 58] and position on the vehicle [2, 20].

Because of declines in sensory abilities elderly pedestrians have difficulties to perceive objects at a distance and correctly estimate speeds [16, 41]. However, adaptation in speed is a main transmitter of implicit forms of communication of vehicles [1]. Having difficulties with this communication form, elderly pedestrians might benefit more from eHMIs (e.g. visual and/or auditory stimuli). But also in the design of explicit forms of communication of different modalities, coding and positioning of information transmission must be adapted to age-related impairments of sensory abilities (e.g. decline of central acuity).

Due to declines in cognitive abilities, elderly pedestrians have difficulties to focus on relevant information, to flexibly distribute their attention and to make timely, correct road-crossing decisions [16]. To enable elderly pedestrians to process the information conveyed correctly and in a timely manner, the information must be presented in an easily graspable form being the result of careful decisions in the relevant design criteria of content, coding and perspective. Another important design criteria to be considered here is the timing of communication [1, 12]. Elderly pedestrians could benefit of an early communication onset, relieving them from decision making under time pressure.

Declines in motor abilites of elderly pedestrians are related to difficulties of adapting a chosen road crossing strategy [32, 41]. In terms of content, AVs should therefore avoid communication that forces elderly pedestrians to (rapidly) adjust their current road crossing strategy. In addition, the immobility of the elderly people's neck must be considered when determining the information position. Finally, an AV needs to have a high contextual understanding of its environment in order to take the elderly pedestrians' lower walking speeds into account and to give them enough time to execute their preferred strategy.

4 CONCLUSION

Despite being a relevant group for pedestrian road safety, current developments of implicit and explicit forms of communication for AVs have neglected the requirements of elderly pedestrians. Age-related impairments contribute to difficulties of elderly pedestrians when crossing a road [16, 17] but this has not been cooperated yet in any communication designs for AVs. The specification of design criteria presented in this paper allows further research to examine the design of implicit and explicit communication for AVs with elderly pedestrians.

Elderly pedestrians seem to perceive AVs as useful [45] or even less risky than being around human-operated traffic [28]. In order to increase the chances of improving road safety of elderly pedestrians, the human-oriented design approach for the elderly pedestrian population should be enhanced and pursued. Further research could investigate compensation strategies for age-related impairments [41] and self-regulation behavior of elderly pedestrians [36] in their interaction with AVs.

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REFERENCES

[1] Claudia Ackermann, Matthias Beggiato, Luka-Franziska Bluhm, Alexandra Löw, and Josef F. Krems. 2019. Deceleration parameters and their application as informal communication signal between pedestrians and automated vehicles. *Transp Res Part F Traffic Psychol Behav* 62 (Apr 2019), 757–768. https://doi.org/10.1016/j.trf.2019.03.006

[2] Claudia Ackermann, Matthias Beggiato, Sarah Schubert, and Josef F. Krems. 2019. An experimental study to investigate design and assessment criteria: What is important for communication between pedestrians and automated vehicles? *Appl Ergon* 75 (Feb 2019), 272–282. https://doi.org/10.1016/j.apergo.2018.11.002

[3] Dovilé Adminaité-Fodor and Graziella Jost. 2020. *How Safe is Walking and Cycling in Europe?* PIN Flash Report 38. European Transport Safety Council.

[4] Georg J. Andersen and AnnJudel Enriquez. 2006. Aging and the detection of observers and moving object collisions. *Psychol. Aging* 21, 1 (Mar 2006), 74–85. https://doi.org/10.1037/0882-7974.21.1.74

[5] Saeed A. Bagloee, Madjid Tavana, Mohsen Asadi, and Tracey Oliver. 2016. Autonomous vehicles: challenges, opportunities, and future implications for transportation policies. *J. Mod. Transport.* 24, 4 (Dec 2016), 285–303. https://doi.org/10.1007/s40534-016-0117-3

[6] Pavlo Bazilinskyy, Dimitra Dodou, and Joost de Winter. 2019. Survey on eHMI concepts: The effect of text, color, and perspective. *Transp Res Part F Traffic Psychol Behav* 67 (Nov 2019), 175–194. https://doi.org/10.1016/j.trf.2019.10.013

[7] Erika Borella, Barbara Carretti, and Rossana De Beni. 2008. Working memory and inhibition across the adult life-span. *Acta Psychol.* 128, 1 (May 2008), 33–44. https://doi.org/10.1016/j.actpsy.2007.09.008

[8] Amos S. Cohen. 2008. Wahrnehmung als Grundlage der Verkehrsorientierung bei nachlassender Sensorik während der Alterung. In *Leistungsfähigkeit und Mobilität im Alter*, B. Schlag (Ed.). TÜV Media GmbH, Cologne, Germany, 65–80.

[9] Mark Colley, Marcel Walch, Jan Gugenheimer, and Enrico Rukzio. 2019. Including People with Impairments from the Start: External Communication of Autonomous Vehicles. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications: Adjunct Proceedings (AutomotiveUI '19)*. September 21 - 25, 2019, Utrecht, Netherlands. ACM Inc., New York, NY, 307–314. https://doi.org/10.1145/3349263.3351521

[10] Maricarmen Cruz-Jimenez. 2017. Normal Changes in Gait and Mobility Problems in the Elderly. *Phys Med Rehabil Clin N Am.* 28, 4 (Nov 2017), 713–725. https://doi.org/10.1016/j.pmr.2017.06.005

[11] Ragnhild J. Davidse. 2006. Older Drivers and ADAS. Which Systems Improve Road Safety? *IATSS Res.* 30, 1 (2006), 6–20. https://doi.org/10.1016/S0386-1112(14)60151-5

[12] Koen de Clerq, Andre Dietrich, Juan Pablo Núnez Velasco, Joost de Winter, and Riender Happee. 2019. External Human-Machine Interfaces on Automated Vehicles: Effects on Pedestrian Crossing Decisions. *Hum Factors* 61, 8 (Dec 2019), 1153–1370. https://doi.org/10.1177/0018720819836343

[13] Debargha Dey, Azra Habibovic, Bastian Pfleging, Marieke Martens, and Jacques Terken. 2020. Color and Animation Preferences for a Light Band eHMI in Interactions Between Automated Vehicles and Pedestrians. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. April 25 - 30, 2020, Honolulu, HI, USA. ACM Inc., New York, NY, 1–13. https://doi.org/10.1145/3313831.3376325

[14] Debargha Dey and Jacques Terken. 2017. Pedestrian Interaction with Vehicles: Roles of Explicit and Implicit Communication. In *Proceedings of the 9th ACM International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '17)*. September 24 - 27, 2017, Oldenburg, Germany. ACM Inc., New York, NY, USA, 109–113. https://doi.org/10.1145/3122986.3123009

[15] Aurélie Dommes and Viola Cavallo. 2011. The role of perceptual, cognitive, and motor abilities in street-crossing decisions of young and older pedestrians. *Ophthal Physl Opt* 31, 3 (Mar 2011), 292–301. https://doi.org/10.1111/j.1475-1313.2011.00835.x

[16] Aurélie Dommes, Viola Cavallo, and Jennifer Oxley. 2013. Functional declines as predictors of risky street-crossing decisions in older pedestrians. *Accid. Anal. Prev.* 59 (Oct 2013), 135–143. https://doi.org/10.1016/j.aap.2013.05.017

[17] Aurélie Dommes, Tristan Le Ley, Fabrice Vienne, Nguyen-Thong Dang, Alexandra Perrot Beaudoin, and Manh Cuong Do. 2015. Towards an explanation of age-related difficulties in crossing a two-way street. *Accid. Anal. Prev.* 85 (Dec 2015), 229–238. https://doi.org/10.1016/j.aap.2015.09.022

[18] Werner Draeger and Dorothée Klöckner. 2001. Ältere Menschen zu Fuß und mit dem Fahrrad unterwegs. In *Mobilität älterer Menschen*, A. Flade, M. Limbourg, and B. Schlag (Eds.). Springer Fachmedien, Wiesbaden, Germany, 41–67. https://doi.org/10.1007/978-3-663-10820-7_4

[19] George Dunbar. 2012. The relative risk of nearside accidents is high for the youngest and oldest pedestrians. *Accid. Anal. Prev.* 45 (Mar 2012), 517–521. https://doi.org/10.1016/j.aap.2011.09.001

[20] Yke B. Eisma, S. van Bergen, S.M. ter Brake, M.T.T. Hensen, Willem J. Tempelaar, and Joost C.F. de Winter. 2020. External Human-Machine Interfaces: The Effect of Display Location on Crossing Intentions and Eye Movements. *Information* 11, 1 (Jan 2020), 1–18. https://doi.org/10.3390/info11010013

[21] Stefanie M. Faas, Lesley-Ann Mathis, and Martin Baumann. 2020. External HMI for self-driving vehicles: Which information shall be displayed? *Transp Res Part F Traffic Psychol Behav* 68 (Jan 2020), 171–186. https://doi.org/10.1016/j.trf.2019.12.009

[22] Michael Falkenstein, Jörg Hoormann, and Joachim Hohnsbein. 2002. Inhibition-related ERP components: variation with age and time-on task. *Journal of Psychophysiology* 16, 3 (2002), 167–175. https://doi.org/10.1027//0269-8803.16.3.167

[23] Myra A. Fernandes, Anda Pacurar, Morris Moscovitch, and Cheryl Grady. 2006. Neural correlates of auditory recognition under full and divided attention in younger and older adults. *Neuropsychologia* 44, 12 (2006), 2452–2464. https://doi.org/10.1016/j.neuropsychologia.2006.04.020

[24] Gunilla Haegerstrom-Portnoy, Marilyn E. Schneck, and John A. Brabyn. 1999. Seeing into Old Age: Vision Function Beyond Acuity. *Optom. Vis. Sci.* 76, 3 (Mar 1999), 141–158. https://doi.org/10.1097/00006324-199903000-00014

[25] Melanie Hahn, Nele Wild-Wall, and Michael Falkenstein. 2011. Age-related differences in performance and stimulus processing in dual task situation. *Brain Res* 1414, 26 (Sep 2011), 66–76. https://doi.org/10.1016/j.brainres.2011.07.051

[26] Ann-Cristin Hensch, Isabel Neumann, Matthias Beggiato, Josephine Halama, and Josef F. Krems. 2019. Steady, flashing, sweeping – An exploratory evaluation of light signals as an eHMI in automated driving. In *Poster presented at the Human Factors and Ergonomics Society Europe Chapter 2019 Annual Conference*. HFES Europe Chapter, Nantes, France.

[27] Carol Holland and Ros Hill. 2010. Gender differences in factors predicting unsafe crossing decisions in adult pedestrians across the lifespan: A simulation study. *Accid. Anal. Prev.* 42, 4 (Jul 2010), 1097–1106. https://doi.org/10.1016/j.aap.2009.12.023

[28] Lynn M. Hulse, Hui Xie, and Edwin R. Galea. 2018. Perceptions of autonomous vehicles: Relationships with road users, risk, gender and age. *Saf Sci* 102 (Feb 2018), 1–13. https://doi.org/10.1016/j.ssci.2017.10.001

[29] Bettina Laugwitz, Theo Held, and Martin Schrepp. 2008. Construction and Evaluation of a User Experience Questionnaire. In *Proceedings of the 4th Symposium of the Workgroup Human-Computer Interaction and Usability Engineering of the Austrian Computer Society (USAB 2008)*. November 20 - 21, 2008, Graz Austria. Springer, Berlin, Heidelberg, Germany, 63–76. https://doi.org/10.1007/978-3-540-89350-9_6

[30] Andreas Löcken, Carmen Golling, and Andreas Riener. 2019. How Should Automated Vehicles Interact with Pedestrians? A Comparative Analysis of Interaction Concepts in Virtual Reality. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '19)*. September 21 - 25, 2019, Utrecht, Netherlands. ACM Inc., New York, NY, 262–274. https://doi.org/10.1145/3342197.3344544

[31] Ulman Lindenberger, Michael Marsiske, and Paul B. Baltes. 2000. Memorizing while walking: increase in dual-task costs from young adulthood to old age. *Psychol Aging* 15, 3 (Sep 2000), 417–436. https://doi.org/10.1037//0882-7974.15.3.417

[32] Régis Lobjois and Viola Cavallo. 2009. The effects of aging on street-crossing behavior: From estimation to actual crossing. *Anal. Prev.* 41, 2 (Mar 2009), 259–267. https://doi.org/10.1016/j.aap.2008.12.001

[33] Sebastien Lord and Nicolas Luxembourg. 2007. The mobility of elderly residents living in suburban territories: mobility experiences in Canada and France. *J. Hous. Elder.* 20, 4 (Oct 2007), 130–121. https://doi.org/10.1300/J081v20n04_07

[34] Ruth Madigan, Sina Nordhoff, Charles Fox, Roja E. Amini, Tyron Louw, Marc Wilbrink, Anna Schieben, , and Natasha Merat. 2019. Understanding interactions between Automated Road Transport Systems and other road users: A video analysis. *Transp Res Part F Traffic Psychol Behav* 66 (Oct 2019), 196–213. https://doi.org/10.1016/j.trf.2019.09.006

[35] Karthik Mahadevan, Sowmya Somanath, and Ehud Sharlin. 2018. Communication Awareness and Intent in Autonomous Vehicle-Pedestrian Interaction. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. April 21 - 26, 2018, Montréal, QC, Canda. ACM Inc., New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3174003

[36] Yoshinori Nakagawa. 2019. Elderly pedestrians' self-regulation failures and crash involvement: The development of typologies. *Accid. Anal. Prev.* 133, Article 105281 (Dec 2019), 13 pages. https://doi.org/10.1016/j.aap.2019.105281

[37] Tobias Niebuhr, Mirko Junge, and Erik Rosén. 2016. Pedestrian injury risk and the effect of age. *Accid. Anal. Prev.* 86 (Jan 2016), 121–128. https://doi.org/10.1016/j.aap.2015.10.026

[38] OECD. 2020. *Elderly population (indicator)*. Retrieved July 30, 2020 from https://data.oecd.org/pop/elderly-population.htm#indicator-chart

[39] Ina Othersen, Antonia S. Conti-Kufner, André Dietrich, Philipp Maruhn, and Klaus Bengler. 2018. Designing for Automated Vehicle and Pedestrian Communication: Perspectives on eHMIs from Older and Younger Persons. In *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2018 Annual Conference*. HFES Europe Chapter, Berlin,Germany, 135–148.

[40] Jennie Oxley, Brian Fildes, Elfriede Ihsen, Judight Charlton, and Ross Day. 1997. Differences in traffic judgements between young and old adult pedestrians. *Accid. Anal. Prev.* 29, 6 (Nov 1997), 839–847. https://doi.org/10.1016/S0001-4575(97)00053-5

[41] Jennifer A. Oxley, Elfriede Ihsen, Brian N. Fildes, Judith L. Charlton, and Ross H. Day. 2005. Crossing roads safely: An experimental study of age differences in gap selection by pedestrians. *Accid. Anal. Prev.* 37 (Sep 2005), 962–971. https://doi.org/10.1016/j.aap.2005.04.017

[42] John Parkin, Benjamin Clark, William Clayton, Miriam Ricci, and Graham Parkhurst. 2018. Autonomous vehicle interactions in the urban street environment: a research agenda. *P I CIVIL ENG-MUNIC* 171, 1 (Mar 2018), 15–25. https://doi.org/10.1680/jmuen.16.00062

[43] Brian J. Pugliese, Benjamin K. Barton, Shane J. Davis, and Gerardo Lopez. 2020. Assessing pedestrian safety across modalities via a simulated vehicle time-to-arrival task. *Accid. Anal. Prev.* 134, Article 105344 (Jan 2020), 10 pages. https://doi.org/10.1016/j.aap.2019.105344

[44] Solmaz Razmi Rad, Concalo Homem de Almeida Correia, and Marjan Hagenzieker. 2020. Pedestrians' road crossing behaviour in front of automated vehicles: Results from a pedestrian simulation experiment using agent-based modelling. *Transp Res Part F Traffic Psychol Behav* 69 (Feb 2020), 101–119. https://doi.org/10.1016/j.trf.2020.01.014

[45] Md Mahmudur Rahman, Shuchisnigdha Deb, Lesley Strawderman, Reuben Burch, and Brian Smith. 2019. How the older population perceives self-driving vehicles. *Transp Res Part F Traffic Psychol Behav* 65 (Aug 2019), 242–257. https://doi.org/10.1016/j.trf.2019.08.002

[46] G. Rinkenauer. 2008. Motorische Leistungsfähigkeit im Alter. In *Leistungsfähigkeit und Mobilität im Alter*, B. Schlag (Ed.). TÜV Media GmbH, Cologne, Germany, 143–180.

[47] Peter Robinson. 2001. Abilities to Learn: Cognitive Abilities. In *Encyclopedia of the Sciences of Learning*, Norbert M. Seel (Ed.). Springer, Boston. https://doi.org/10.1007/978-1-4419-1428-6_620

[48] Alexandros Rouchitsas and Hakan Alm. 2019. External Human-Machine Interfaces for Autonomous Vehicle-to-Pedestrian Communication: A Review of Empirical Work. *Front. Psychol.* 10, 2757 (Dec 2019), 1–12. https://doi.org/10.3389/fpsyg.2019.02757

[49] Timothy A. Salthouse. 1996. The processing-speed theory of adult age differences in cognition. *Psychol Rev.* 103, 3 (Jul 1996), 403–428. https://doi.org/10.1037/0033-295x.103.3.403

[50] William Schiff, Rivka Oldak, and Varsha Shah. 1992. Aging person's estimates of vehicular motion. *Psychol. Aging* 7, 4 (Dec 1992), 518–525. https://doi.org/10.1037//0882-7974.7.4.518

[51] Bernhard Schlag. 2008. Wie sicher sind die Älteren im Straßenverkehr? In *Leistungsfähigkeit und Mobilität im Alter*, B. Schlag (Ed.). TÜV Media GmbH, Cologne, Germany, 19–36.

[52] Allison B. Sekuler, Patrick J. Bennett, and Mortimer Mamelak. 2000. Effects of aging on the useful field of view. *Experimental aging research* 26, 2 (Apr 2000), 103–120. https://doi.org/10.1080/036107300243588

[53] Ka-Chun Siu, Li-Shan Chou, Ulrich Mayr, Paul van Donkelaar, and Marjorie H. Woollacott. 2008. Does inability to allocate attention contribute to balance constrains during gait in older adults? *J Gerontol A Biol Sci Med Sci.* 63, 12 (Dec 2008), 1364–1369. https://doi.org/10.1093/gerona/63.12.1364

[54] Robert J. Snowden and Emma Kavanagh. 2006. Motion perception in the aging visual system: minimum motion, motion coherence, and speed discrimination thresholds. *Perception* 35, 1 (Jan 2006), 9–24. https://doi.org/10.1068/p5399

[55] Sergiu C. Stanciu, David W. Eby, Lisa J. Molnar, Renée M. St. Louis, Nicole Zanier, and Lidia P. Kostyniuk. 2018. Pedestrians/Bicyclists and Autonomous Vehicles: How Will They Communicate? *Transp. Res. Rec.* 2672, 22 (Dec 2018), 58–66. https://doi.org/10.1177/0361198118777091

[56] Susanne Tittlbach. 2002. *Entwicklung der körperlichen Leistungsfähigkeit. Eine prospektive Längsschnittstudie mit Personen im mittleren und späteren Erwachsenenalter.* Ph.D. Dissertation. Faculty of Humanities and Social Sciences, Karlsruhe Institute of Technology.

[57] Isabelle Tournier, Aurélie Dommes, and Viola Cavallo. 2016. Review of safety and mobility issues among older pedestrians. *Accid. Anal. Prev.* 91 (Jun 2016), 24–35. https://doi.org/10.1016/j.aap.2016.02.031

[58] Annette Werner. 2018. New Colours for Autonomous Driving: An Evaluation of Chromaticities for the External Lighting Equipment of Autonomous Vehicles. *Colour Turn* 1 (2018), 1–14. https://doi.org/10.25538/tct.v0i1.692

[59] Nele Wild-Wall, Joachim Hohnsbein, and Michael Falkenstein. 2007. Effects of aging on cognitive task preparation as reflected by event-related potentials. *Clin Neurophysiol.* 118, 3 (Mar 2007), 558–569. https://doi.org/10.1016/j.clinph.2006.09.005

[60] Giuseppe A. Zito, Dario Cazzoli, L. Scheffler, Michael Jäger, René Müri, Urs P. Mosimann, T. Nyffeler, Fred W. Mast, and Tobias Nef. 2015. Street crossing behavior in younger and older pedestrians: an eye- and head-tracking study. *BMC Geriatr* 15, 176 (Dec 2015), 1–10. https://doi.org/10.1186/s12877-015-0175-0

A VIDEO

A video presentation on this position paper is online at YouTube (see https://youtu.be/JlRGugx_q34) and can be downloaded in full resolution from this URL: https://hessenbox.tu-darmstadt.de/getlink/fiVPPgYoo1ePGVbYiayXpfnV/.