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21 **How speed and visibility influence preferred headway distances in highly automated**
22 **driving**

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49 **Abstract**

50 While the introduction of highly automated vehicles promises lower accident numbers, a main
51 requirement for wide use of these vehicles will be the acceptance by drivers. In this study a
52 crucial variable for the acceptance of highly automated vehicles, the vehicle to vehicle
53 distance expressed in time headway, was researched in a driving simulator. Research has
54 shown that time headway distances, perceived as comfortable in self-driving and assisted
55 driving with adaptive cruise control, remain constant over a range of different speeds. This
56 study aims to test these findings for highly automated driving. Since time headway is
57 perceived visually, the driving situation was varied to investigate the influence of visibility on
58 the subjective comfort of the driver in a highly automated driving situation. In a within-
59 subject design, drivers followed a passenger car in clear weather conditions, the same
60 passenger car in fog which occluded parts of the traffic environment, as well as a truck that
61 occluded the lane ahead, also in clear weather condition. Subjective comfort of drivers in each
62 condition was rated with a haptic rating lever.

63 Results suggest that comfortable time headway following distances in highly automated
64 driving are not constant over different speeds, but that these distances decrease with
65 increasing speed. Reduced visibility generally led to a shift in comfortable following distances
66 towards larger headways. These results have implications for the introduction of highly
67 automated vehicles and their time headway adjustments, which will need to be adaptive to
68 speed and visibility in the road environment.

69

70 **1. Introduction**

71 Past research suggests that time headway is a variable held constant by individual drivers in
72 self-driving (Siebert, Oehl, & Pfister, 2014; Siebert, Oehl, Bersch, & Pfister, 2017; Van
73 Winsum & Heino, 1996), and the individual choice of time headway has been related to the
74 drivers' awareness of risk and comfort (Lewis-Evans, De Waard, & Brookhuis, 2010).

75 However, there has been comparatively little research on the influence of longitudinal vehicle
76 to vehicle distances of highly automated vehicles on the subjective experience of drivers, with
77 a small number of studies pointing to the importance of time headway adjustments in highly
78 automated driving (Bellem, Schönenberg, Krems, & Schrauf, 2016; De Waard, Van der Hulst,
79 Hoedemaeker, & Brookhuis, 1999). Since drivers will not be able to regulate their following
80 distance in highly automated driving as freely as in self-driving, it is important to understand

81 how time headway distances need to be adjusted for highly automated driving, without drivers
82 feeling uncomfortable. Therefore, this study tested how results of constant time headway
83 following from self- and assisted driving translate to highly automated driving. A general
84 preference for constant time headway following in highly automated driving would imply that
85 the complete secession of control by the driver of the car does not alter the effect of preferred
86 constant time headways found in self- and assisted-driving. In turn, this would allow car
87 manufacturers to program highly automated vehicles to follow at a constant time headway
88 over a broad speed range.

89 Another goal of this study was to investigate the influence of different visibility conditions on
90 preferred following distances in highly automated driving. Since time headway is the result of
91 a visual estimation of the vehicle to vehicle distance divided by an estimation of the vehicle
92 speed, the accuracy of an individual's time headway estimation depends on the visibility
93 condition. Effects of changing following distances under adverse visibility on car following
94 have been studied for self-driving, and we hope to extend this research to highly automated
95 driving.

96

97 **1.1 Constant time headway following**

98 A large number of studies have found that drivers follow other vehicles with a constant time
99 headway at different speeds, and prefer constant time headway following to non-constant
100 following when presented with a number of time headways at different speeds (Ayres, Li,
101 Schleuning, & Young, 2001; Siebert et al., 2014, 2017; Taieb-Maimon & Shinar, 2001; Van
102 Winsum & Heino, 1996). Siebert et al. (2014, 2017) researched car following preferences for
103 the use of adaptive cruise control and found stable individual time headway preferences. Most
104 preferred headways in self- and assisted-driving are found in the range of one to two seconds
105 in simulated as well as in real-life driving, although preferred time headways of individual
106 drivers differ. In all earlier studies on the relation between the subjective experience of drivers
107 and time headway, drivers either had complete control over the vehicle (Ayres et al., 2001;
108 Taieb-Maimon & Shinar, 2001; Van Winsum & Heino, 1996), or were actively controlling
109 the steering wheel in studies where an adaptive cruise control system was implemented
110 (Siebert et al., 2014, 2017). It is therefore unclear how the complete absence of active control
111 over the vehicle in highly automated driving influences the subjective experience of time
112 headways. Researchers have hypothesized that speed influences the subjective experience of

113 drivers in highly automated driving differently than in self- or assisted driving, due to a
114 lack of immediate controllability of the driving situation (De Vos, Theeuwes, Hoekstra, &
115 Coëmet, 1997; Telpaz, et al., 2018).

116

117 **1.2 Driving in fog and behind larger vehicles**

118 Van Winsum (1999) postulates in his mathematical model of human car following that a
119 reduced visibility in the driving environment due to fog or rain should in theory lead to an
120 increase in time headway “as an increase of the safety margin to compensate for later
121 detections of decelerations of lead vehicles” (p. 209). However, researchers have found
122 conflicting results for following behavior during fog. While in some studies drivers increase
123 their time headway when visibility is reduced (Van der Hulst, Rothengatter, Meijman, 1998)
124 and their perceived risk is increased (Saffarian, Happee, De Winter, 2012), in other studies
125 drivers follow closer when the visibility is reduced due to fog (Al-Ghamdi, 2007).

126 Researchers have also found interindividual differences when driving in heavy fog (visibility
127 limit of 41 m), with some drivers reducing time headway to within the visibility range of the
128 lead vehicle, and other drivers increasing their time headway, thereby losing sight of the lead
129 vehicle (Broughton, Switzer, and Scott, 2007).

130 Apart from reduced visibility of the driving environment due to weather, forward visibility
131 can also be reduced when following large vehicles such as trucks or busses. For following
132 larger vehicles there is no clear effect on following distances compared to following normal
133 sized vehicles in self-driving. Studies have found increased time headways (Green & Yoo,
134 1999; Wasielewski, 1981), decreased time headways (Brackstone, Waterson, & McDonald,
135 2009; Sayer, Mefford, & Huang, 2000), and increasing as well as decreasing time headways
136 depending on driving speed (Duan, Li, & Salvendy, 2013). Since this study is the first to
137 compare following distances during clear and reduced visibility in highly automated driving,
138 we base our hypotheses on Van Winsum’s mathematical model of human car following
139 (1999), and assume that a decrease in visibility will necessitate and increase in time headway
140 distances.

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144 **1.3 Using a haptic lever for feedback on subjective experience in driving**

145 Different subjective variables have been used as dependent variables when participants are
146 asked to rate their subjective experience of different time headways. Earlier studies have
147 shown that subjective variables highly correlate with each other when time headways are
148 rated (Lewis-Evans et al., 2010; Siebert et al., 2014). In this study, comfort was chosen as the
149 dependent variable because it can be described in a positive and negative valence by the
150 words comfort (German: *angenehm*) and discomfort (German: *unangenehm*). Due to
151 translation imprecision, the German terms could also be translated as *pleasant* and *unpleasant*.
152 Furthermore, a bi-directional haptic lever was used instead of single items in a likert-scale
153 format used by Lewis-Evans et al. (2010) and Siebert et al. (2014). An advantage of this
154 method is the simultaneous evaluation of the vehicle to vehicle distance, compared to a
155 retrospective rating by a subsequent questionnaire. Additionally, the lever allows the
156 participants to focus on the leading vehicle while rating the vehicle to vehicle distance since
157 the lever can be adjusted without looking at it. The type of lever used in this study has been
158 positively evaluated for linearity of ratings (Vehrs, 1986). A study by Charlton, Starkey,
159 Perrone, and Isler (2014) showed that participants are able to concurrently rate the risk of a
160 traffic situation by using a haptic risk-meter, similar in function to the lever used in this study.

161

162 **1.4 Goals of this study**

163 In this driving simulator study, the forward visibility of drivers in a highly automated vehicle
164 was systematically varied at different speeds. To assess the impact of different time headways
165 and reduced visibility on the subjective experience of the participants, drivers indicated their
166 subjective level of comfort by moving a bi-directional haptic lever with their right hand.
167 Participants were then presented with different vehicle to vehicle distances and the lever
168 position was recorded continuously for these different distances.

169 We expected that in highly automated driving (1) speed does influence the comfort ratings for
170 specific time headways and (2) reduced visibility reduces subjective comfort ratings for
171 distances when compared to the clear visibility condition.

172

173

174 2. Method

175 2.1 Participants

176 Thirty-nine participants took part in this study. Due to technical difficulties with the scaling
177 lever, 4 participants were excluded from the analysis. All results reported in this paper are
178 based on the sample of the 35 participants where no technical difficulties occurred. Of these
179 35 participants, 17 were female and 18 were male. Participants had a mean age of $M = 22.46$
180 years ($SD = 5.84$). All participants were in possession of a valid driver's license, that they had
181 acquired an average of $M = 4.96$ years ($SD = 5.86$) before the study. On average, participants
182 estimated to drive $M = 8820.57$ kilometers per year ($SD = 18902.6$) with a minimum of 20
183 and a maximum of 100000 kilometers. The average accumulated driving experience of the
184 participants was approximately 108,000 kilometers. About one third of the participants owned
185 a car, and more than 50% of the participants used their own or another car at least once a
186 week. Thirty-four participants were right-handed, with one participants being ambidextrous.
187 Participants were recruited from the student body of the Leuphana University Lüneburg as a
188 convenient sample. For their participation, participants were given "study-subject hours" that
189 they have to acquire during their time at the university.

190

191 2.2 Experimental design

192 In this experiment, visibility was varied threefold (clear vs. truck vs. fog), speed was varied
193 threefold (50km/h vs. 100km/h vs. 150km/h), and time headway was varied tenfold (0.5 vs.
194 1.0 vs. 1.25 vs. 1.5 vs. 1.75 vs. 2.0 vs. 2.5 vs. 3.0 vs. 3.5 vs. 4.0). Two extra time headway
195 increments (1.25 and 1.75 seconds) were added to more finely represent typical time
196 headways found in earlier studies (Siebert et al., 2014, 2017). The resulting 90 experimental
197 conditions were grouped in 9 blocks, each block consisting of a randomized order of ten time
198 headways for the same visibility and speed. These 9 blocks were then randomly presented to
199 participants. All participants were presented with the 90 experimental conditions in a within-
200 subject design.

201 Each experimental condition lasted 10 seconds, and each experimental block lasted about 120
202 seconds. There were short pauses of about 2-3 seconds between the conditions within each
203 block, and longer pauses of 20-30 seconds between blocks, when a new block was loaded into
204 the driving simulation software.

205 **2.3 Driving simulator and driving environment**

206 The study was conducted at the Leuphana University Lüneburg in a fixed-base driving
207 simulator cabin resembling a Volkswagen Golf 4 GTI with automatic transmission. To
208 simulate the driving environment, SCANeR Studio Driving Simulation Software version 1.4
209 from Oktal was used. The driving environment was projected onto three screens in front of
210 the simulator cabin for a total resolution of 3072x768 pixels with three video projectors. Each
211 single screen had a size of 1.4 x 1.4 meters. The outer screens were positioned at an angle of
212 120° to the center screen. The driver seat was positioned 2 meters from the center screen,
213 resulting in a horizontal field of view of approximately 110° and a vertical field of view of
214 approximately 30°. The physical and simulated eye height of the participants was 1.25m. The
215 simulated car model was a compact car, a Citroën C4. The speedometer of the simulator was
216 inactive during the experiment. Simulation data were saved with a frequency of 20 Hz.

217 Three driving environments were programmed for this study, with each environment
218 representing a road type where a speed of 50, 100, or 150km/h could be expected. The
219 50km/h driving environment resembled an inner city road with one lane in each direction. The
220 100km/h driving environment was modelled after a German rural road, with two lanes in each
221 direction, with opposing lanes divided by a solid line. The 150km/h condition was modelled
222 after a German “Autobahn”, a highway road where the advised speed is 130km/h, but
223 generally there is no enforced speed limit. In this condition there were three lanes in each
224 direction, and opposing traffic was separated by a guard railing. Each environment had only
225 minimal road curvature, no slope, and sparse oncoming traffic. There were no side-streets in
226 any of the road environments and there was no cross traffic by pedestrians. Road side
227 buildings and trees had a minimum distance of 20 meters to the side of the road. The
228 participant’s vehicle and the lead vehicle always drove in the right-most lane.

229 Screenshots of the three visibility conditions are shown in Figure 1. The lead vehicle in the
230 clear condition was a compact car, the lead vehicle in the truck condition was a truck, and the
231 lead vehicle in the fog condition was the same compact car as in the clear condition. The fog
232 in the fog condition was set to a range of 200 m, resulting in light fog with a visibility limit of
233 200 m.



234

235 Figure 1. Screenshots of the center projection of the three visibility and three speed conditions
 236 for a time headway of 2 seconds: fog & 50km/h (left), truck & 100km/h (middle), clear &
 237 150km/h (right).

238

239 2.4 Procedure

240 After participants arrived at the simulator, they filled out a short demographic questionnaire
 241 and were then seated in the driver’s seat of the simulator. The experimenter then explained the
 242 use of the simulator, and participants’ task in the experiment. The instruction for using the
 243 rating lever was as follows (translated from German):

244 “Today you will be shown multiple driving situations in the driving simulator. During these
 245 situations, you do not need to control the car, as the car drives by itself. You do not need to
 246 steer, brake, or accelerate. Next to you there is a lever that can be moved in two directions, to
 247 the front and to the back. You will feel a light resistance that tries to automatically move the
 248 lever to a middle position. The lever position at the maximum front position represents
 249 “uncomfortable” (German “unangenehm”), the middle lever position represents “neutral”
 250 (German “neutral”), and the maximum back position is “comfortable” (German “angenehm”).
 251 Now take the lever into your hand and familiarize yourself with it by moving it to the front
 252 and the back multiple times. Now try some lever positions without looking at the lever. In the
 253 following you will see multiple consecutive driving situations. Please indicate the intensity of
 254 your feelings toward the distance to the lead vehicle, by adjusting the lever between
 255 “comfortable”, “neutral”, and “uncomfortable” and keeping the lever in this position for the
 256 whole driving situation. Please only rate the distance to the lead vehicle and not the other
 257 traffic or the driving environment.”

258 A figure with the lever positions with the “comfortable”, “neutral”, and “uncomfortable”
 259 position was shown to participants during the explanation of the lever positions. This part of
 260 the instruction was followed by a short training in which the experimenter instructed the

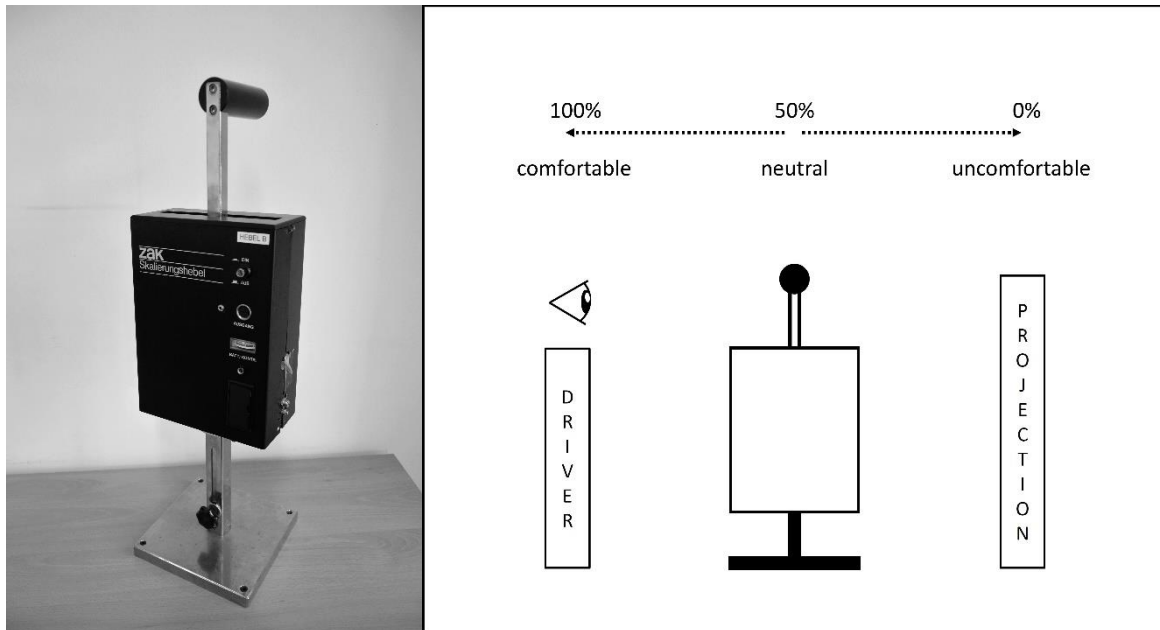
261 participant to imagine a positive, a negative, and a neutral event and use the lever to rate his
262 or her feelings during this event. The participant was then reminded to focus their gaze on the
263 driving situations and not on the lever and the first block of driving situations was started.

264

265 **2.5 Comfort rating lever**

266 Participants rated their subjective experience of the vehicle to vehicle distance on a bi-
267 directional haptic lever (Figure 2). The lever used in this study is an adapted version of the
268 “Vehrs-Hebel” (engl. “Vehrs-Lever”), developed by Wolfgang Vehrs (1986) for the non-
269 verbal rating of stimuli. The self-centering lever-arm protrudes out of the top end of a heavy
270 base that houses the mechanics of the lever. Using an orthogonally placed handle at the top,
271 the lever can be moved within 15 cm, i.e., for 7.5cm from its middle position to each edge of
272 the box. Placed under the driving simulator cabin, the lever arm protrudes out of the middle
273 console in front of the gearstick. Tests on the use of the lever for ratings of subjective
274 experiences by Vehrs (1986) as well as a pretest by the authors of this study suggest that
275 participants are able to express their subjective experience accurately with the help of the
276 lever. The lever position is saved as a percentage value with a frequency of 20 Hz. A
277 “comfortable” lever rating, i.e., a participant pulls the lever as close toward him- or herself as
278 possible, results in a 100% value. A “neutral” lever rating, where the lever is positioned in the
279 middle, results in a 50% value. An “uncomfortable” rating where a participant pushes the
280 lever as far away as possible from him- or herself results in a 0% value (Figure 2).

281 The direction of valence of lever ratings (see 2.4) was chosen for two reasons. First, it is more
282 natural to have “uncomfortable” ratings defined as a lever push away from the body, and
283 “comfortable” ratings as a pulling movement towards the own body (Chen & Bargh, 1999;
284 Solarz, 1960). Second, since time headways for a given speed are represented as gaps between
285 the participant’s vehicle and the lead vehicle, the lever movement could in theory just copy
286 this gap between the two vehicles. In this case, the lever would present the position of the lead
287 vehicle. Defining the lever ratings in a way that prohibits this replication of the lead vehicle
288 position with the lever helps to prevent this effect. Apart from the exact lever position, the
289 median of all lever ratings is an indicator if the majority of participants rates a distance as
290 comfortable (median position > 50%) or uncomfortable (median position < 50%).



291

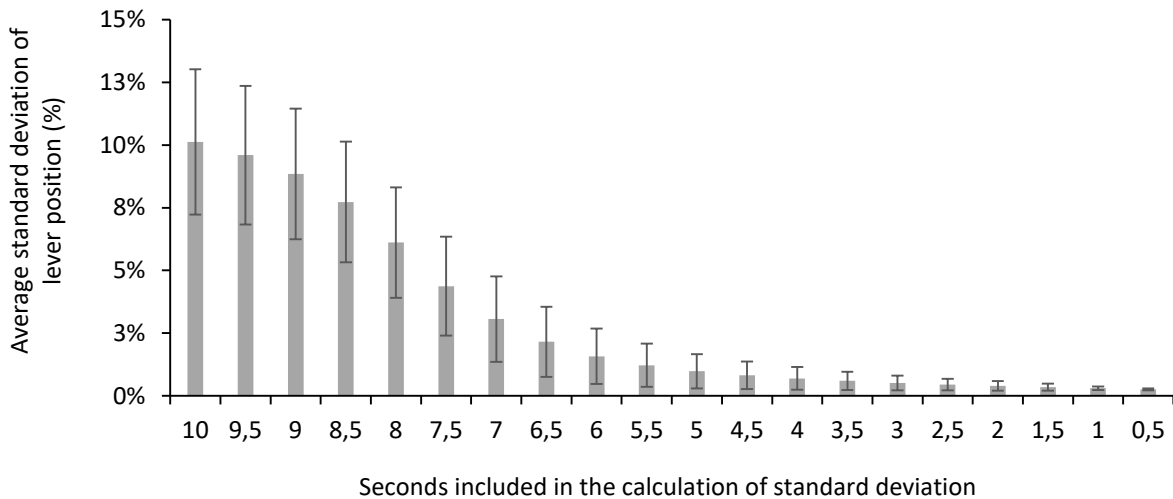
292 Figure 2. Rating lever and scaling direction.

293

294 2.6 Analysis

295 The raw data output of the lever were pre-processed before any calculations were conducted.
 296 Since conditions were presented consecutively, the initial lever position of a condition was
 297 influenced by the final lever position of the preceding condition. As participants were
 298 instructed to maintain a lever position once the lever was at the intended position, we looked
 299 at the standard deviation of the lever position, as it indicates movement of the lever.

300 The standard deviation of all ratings in this study was plotted, including each condition and
 301 each participant, resulting in one average of standard deviation for 10 seconds of rating. These
 302 10 seconds were consecutively shortened in 0.5 second steps starting from the beginning, until
 303 there were only the last 0.5 seconds of the condition left. The resulting data (Figure 3) showed
 304 that standard deviation in the lever data decreases as the first few seconds of each condition
 305 are eliminated. From Figure 3 it can be assumed that the majority of participants require about
 306 5 seconds to arrive at the intended lever position. Due to this, the lever data of the first five
 307 seconds of each condition was not included in the calculation of the lever position. Only the
 308 last 5 seconds (100 data points) of each condition are averaged and used as the comfort rating
 309 for a given condition.



310

311 Figure 3. Average standard deviation of the lever position for different condition times,
 312 reduced by 0.5 second increments from the start of the condition (error bars show the standard
 313 deviation).

314 All rating data were analyzed by a three-way (3x3x10) repeated measures analysis of variance
 315 (ANOVA), with visibility (within-subjects; clear vs. fog vs. truck), speed (within-subjects;
 316 50km/h vs. 100km/h vs. 150km/h), and time headway (within-subjects; 0.5 vs. 1.0 vs. 1.25 vs.
 317 1.5 vs. 1.75 vs. 2.0 vs. 2.5 vs. 3.0 vs. 3.5 vs. 4.0) as the independent variables and comfort
 318 (rated through the lever) as the dependent variable.

319

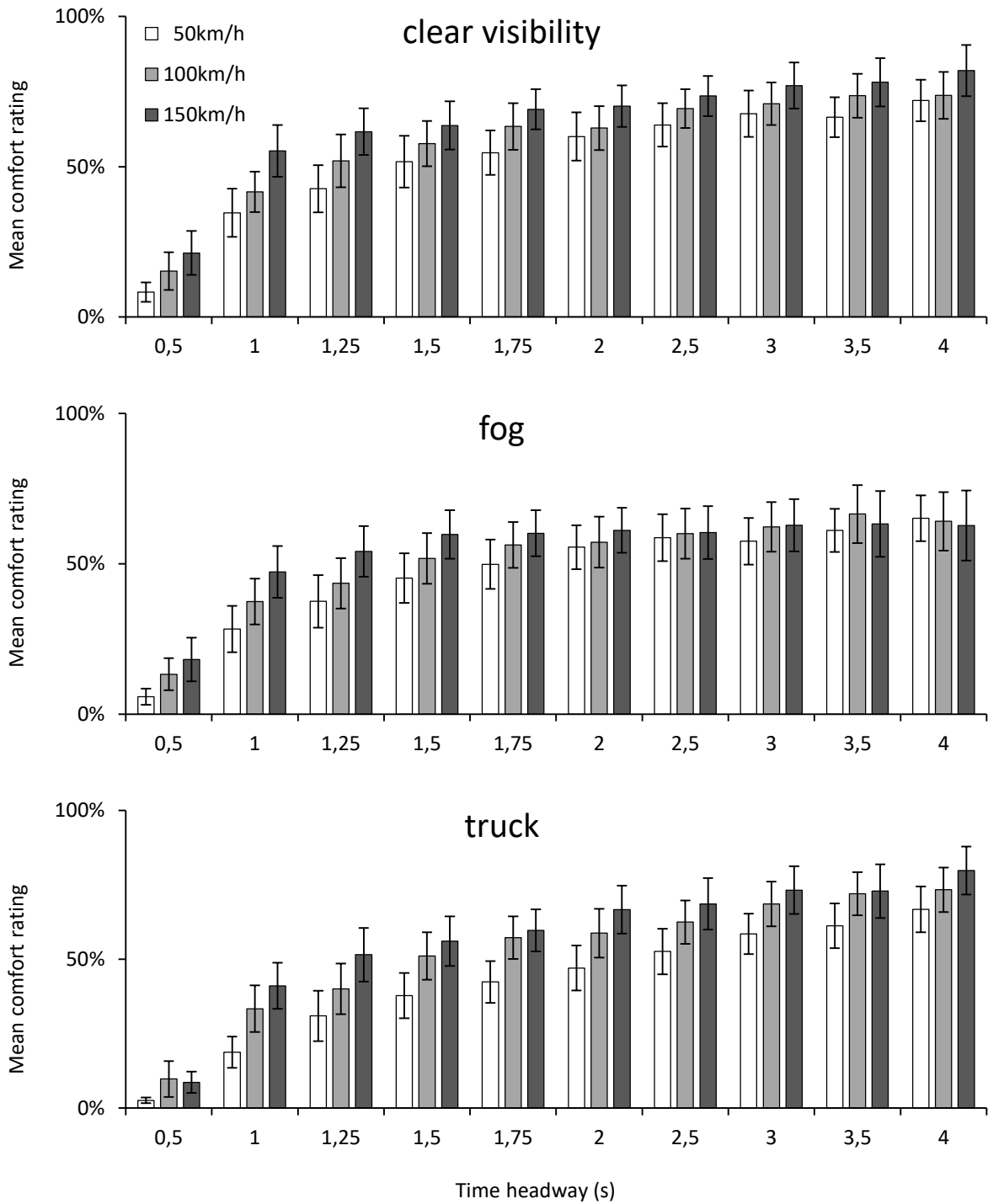
320 3. Results

321 3.1 Influence of speed on comfortable time headways

322 Mean comfort ratings for time headways under different visibility and speed conditions are
 323 presented in Figure 4. We assumed that speed does influence comfort ratings for specific time
 324 headways. The influence of speed on comfort ratings was tested in a three-way ANOVA,
 325 comparing speed as one of the factors at 50, 100 and 150 km/h. Since Mauchly's Test
 326 revealed that the assumption of sphericity had been violated for the main effect of speed ($\chi^2(2)$
 327 = 8.92, $p < .012$), Greenhouse-Geisser corrected degrees of freedom were used ($\epsilon = .81$).
 328 There was a significant main effect of speed on comfort ratings of time headways ($F_{(1.62, 54.98)}$
 329 = 42.22, $p < .01$, $\eta_p^2 = .55$). For nearly all time headways, participants rated following at
 330 lower speeds as less comfortable than following at higher speeds (Figure 4). Comfort in the
 331 clear visibility condition (top of Figure 4) was lowest for the 50km/h condition, followed by
 332 the 100km/h condition, with the 150km/h condition rated as the most comfortable on average.
 333 This difference in ratings can also be observed for the fog and the truck condition, where time

334 headways of lower speeds are rated as less comfortable when compared to the same time
 335 headways at higher speeds. Post-hoc tests using Bonferroni correction for multiple
 336 comparisons revealed significant differences between comfort ratings of all three speed
 337 conditions (all $p < .01$).

338



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342 Figure 4. Mean comfort ratings for different time headways at 50, 100, and 150km/h and three
 343 visibility conditions (error bars show the 95% confidence interval).

344 **3.2 Influence of visibility on comfortable time headways**

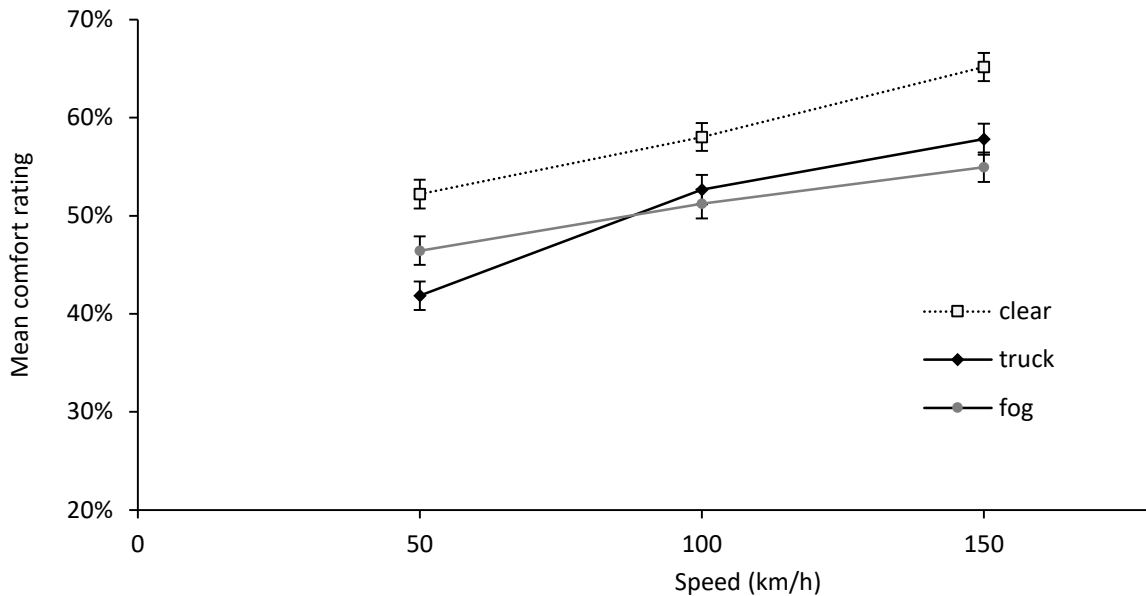
345 We hypothesized that reduced visibility leads to a decrease in comfort ratings of time
346 headways when compared to clear visibility. To test the influence of visibility on comfort
347 ratings, three visibility conditions (clear vs. fog vs. truck) were compared as one factor in a
348 three-way ANOVA. There was a significant main effect of visibility on comfort ratings of
349 time headways ($F_{(2, 68)} = 16.87, p < .01, \eta_p^2 = .33$). Post-hoc tests using Bonferroni correction
350 for multiple comparisons revealed that comfort in the clear visibility condition is significantly
351 higher than in the truck and the fog condition (both $p < .01$). There was no significant
352 difference between comfort ratings of the truck and the fog condition ($p = 1.0$).

353 Descriptively, participants rated shorter time headways (< 3 s) in the fog condition as more
354 comfortable than in the truck condition. However, for larger time headways (≥ 3 s) following
355 in fog was rated as less comfortable than following a truck. Furthermore, comfort ratings for
356 the clear and truck visibility conditions increase with increasing time headways, while
357 comfort ratings for the fog condition remain more constant even when time headway
358 increases. Due to this effect, large time headways are less comfortable in a foggy environment
359 than in the truck or clear visibility condition.

360 **3.3 Interaction of visibility and speed**

361 The ANOVA revealed a significant interaction for the influence of visibility and speed on
362 comfort ratings ($F_{(4, 136)} = 2.86, p = .026, \eta_p^2 = .078$). An interaction graph with a shortened y-
363 axis for better visibility is plotted in Figure 5.

364



365

366 Figure 5. Interaction graph for mean lever ratings for all visibility and speed conditions
 367 (please note the shortened y-axis). Error bars show the 95% confidence interval.

368 In Figure 5 the main effect of speed is visible, comfort generally increases with higher speeds.

369 A difference between the clear condition and reduced visibility conditions can also be
 370 observed, reduced visibility leads to a decrease in comfort, when compared to the clear
 371 visibility condition (all $p < .01$ after Bonferroni correction for multiple comparisons).

372 Between the two reduced visibility conditions however, an interaction between visibility and
 373 speed can be observed descriptively. For the 100 and 150km/h condition, comfort ratings of
 374 the truck and fog condition are descriptively similar and do not significantly differ (all
 375 $p > .05$). However, the mean comfort ratings of the truck condition at 50km/h are
 376 descriptively lower than ratings for the fog condition of the same speed (Figure 5).

377 Calculating a separate repeated-measure ANOVA for the 50km/h condition however does not
 378 show a significant difference between the two reduced visibility conditions, as it just fails to
 379 be significant at $p = 0.57$ after Bonferroni correction for multiple comparisons.

380

381 3.4 Comfortable vs. uncomfortable time headways

382 Through descriptively analyzing the median lever position for an individual experimental
 383 condition, it is possible to determine if a majority of participants rated a given time headway
 384 as comfortable or uncomfortable. Therefore, median lever ratings can be used to descriptively

385 quantify the influence of speed and visibility changes on comfort ratings of time headways.
386 Median lever positions for all conditions are presented in Table 1.

387 For example, in the clear condition at 50km/h, the majority of participants rate time headways
388 of 1.5 seconds and higher as comfortable, i.e. the median lever rating for these time headways
389 is higher than 50% indicating comfortable distances (Figure 2). For 100km/h this threshold
390 shifts to 1.25 seconds, i.e. with a speed increase of 50km/h the time headway distance can be
391 reduced by 0.25 seconds without the majority of participants perceiving the distance as
392 uncomfortable. With an additional increase of the speed to 150km/h the time headway
393 distance again can be reduced by 0.25 seconds, resulting in a following distance of 1.0
394 seconds that is still perceived as comfortable by a majority of participants. For reduced
395 visibility conditions, i.e. driving in fog or behind a truck, a similar effect of speed can be
396 found. With increasing speed, time headway following distances can be decreased without the
397 majority of participants perceiving the distances as uncomfortable (see Table 1).

398 For a reduced visibility road environment, it is necessary to increase time headway. At
399 50km/h, time headway needs to be increased by 1 second when a driver is transferring from
400 e.g. a clear visibility environment, to a foggy road environment, or the lead car changes from
401 a passenger car to a truck. At higher speeds, this shift is less pronounced but still present
402 (Table 1). Through Table 1 it is possible to exactly quantify how time headways need to be
403 changed for varying speeds and visibility.

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411 Table 1. Median lever ratings for different time headways (TH), speeds, and visibility
 412 conditions.

TH	50km/h			100km/h			150km/h		
	clear	fog	truck	clear	fog	truck	clear	fog	truck
0.5	2.8%	1.9%	1.6%	9.2%	6.1%	2.4%	14.8%	12.0%	3.5%
1.0	29.4%	23.9%	17.2%	42.4%	35.1%	25.6%	51.4%	43.8%	38.2%
1.25	38.8%	34.6%	24.6%	51.5%	40.6%	34.7%	56.2%	51.7%	45.9%
1.5	51.0%	42.5%	35.5%	52.0%	44.6%	43.7%	58.6%	60.2%	51.5%
1.75	51.5%	44.6%	39.4%	56.2%	51.4%	51.5%	69.1%	60.4%	52.4%
2.0	52.2%	49.9%	44.6%	58.0%	51.5%	52.4%	66.6%	56.3%	63.4%
2.5	60.3%	52.1%	51.9%	66.1%	57.0%	52.0%	75.7%	59.5%	69.1%
3.0	65.0%	51.6%	57.1%	67.6%	59.4%	62.7%	83.7%	64.5%	74.6%
3.5	66.4%	55.8%	56.9%	75.9%	68.7%	70.9%	88.1%	56.4%	81.4%
4.0	72.5%	61.3%	65.9%	72.8%	68.3%	75.2%	97.0%	62.4%	96.4%

Comfortable ratings with median lever position > 50% in bold.

413

414 4. Discussion

415 In this study we examined the influence of different time headways on subjective comfort
 416 when following another vehicle with different speeds under different visibility conditions in a
 417 highly automated vehicle. In our first hypothesis we postulated that speed would influence the
 418 subjective comfort for a given time headway. Our data supports this hypothesis, time
 419 headways at lower speeds were rated as less comfortable than the same time headways at
 420 higher speeds. This result stands in contrast to results of earlier studies on self- and assisted-
 421 driving, where the subjective experience of a given time headway was not influenced by
 422 speed (Siebert et al., 2014, 2017). The assumption of equal comfort for identical time
 423 headways can therefore not be extended to highly automated driving. It is important to keep in
 424 mind that this study differs from earlier studies on time headway and subjective experience, in

425 that the simulated car in this study was highly automated. In contrast to earlier studies (see
426 Section 1.1.), participants did not have any control over the car, which could have a general
427 effect on perceived comfort levels for time headways. If there was a simple effect of control,
428 i.e. that less control (as in highly automated driving) leads to less comfort for a given time
429 headway, this effect would be constant for different speeds. This simple effect would
430 therefore not lead to the results found in this study. Our analysis of median lever ratings
431 reveals that with an increase in speed of 50km/h, time headway distances can be reduced by
432 0.25 seconds without the majority of participants perceiving the distance as uncomfortable.
433 Although the relative validity of driving simulators has been established for speed and vehicle
434 to vehicle distances (Godley, Triggs, & Fildes, 2002; Risto, & Martens, 2014), the exact time
435 headway distances found in this study might not be directly transferable to real life driving.
436 Nonetheless, our results indicate that time headways in highly automated driving will need to
437 be adaptive to speed.

438 In our second hypothesis we postulated that reduced visibility leads to a decrease in comfort
439 ratings when compared to the same distances in the clear visibility condition. In this study,
440 participants rated time headways as significantly less comfortable when visibility was reduced
441 by a truck or due to fog, supporting our hypothesis. Our analysis of median comfort ratings
442 shows that reduced visibility requires an increase in up to 1 second time headway, to maintain
443 a comfortable rating of the distance by a majority of the participants. As discussed earlier,
444 research on self-driving has not found a consistent effect of reduced visibility on car
445 following behavior. The results of this study appear to support findings of increased headway
446 following in reduced visibility conditions, and expand these findings to highly automated
447 driving.

448 While there was no significant difference of comfort ratings between the fog and the truck
449 condition, there was a significant interaction of visibility and speed. Although the effect just
450 failed to be significant in posthoc testing, following a truck was descriptively rated as less
451 comfortable than following in fog in the 50km/h condition. This descriptive effect was not
452 present in the 100 or 150km/h condition.

453 A descriptive effect of fog on comfort ratings of time headways can be observed for larger
454 time headways. While comfort increases with time headways in the truck condition, comfort
455 ratings stay more constant in the fog condition, although time headway distances are
456 increasing. This effect is most pronounced in the 150km/h condition. A possible explanation
457 for this effect is the visibility limit of 200 meters set for the fog condition in this study.

458 Although even in the largest time headway conditions of four seconds the lead vehicle is
459 always visible (as the largest distance of the 150km/h condition is 166.66 meters), the lead
460 vehicle is close to the edge of the visible driving environment. While this does not directly
461 influence the following car, participants might anticipate a potential loss of visibility of the
462 lead vehicle. This might be the onset of the effect of close following to keep eye-contact to
463 the lead vehicle, found by Broughton et al. (2007). The influence of the visibility range of
464 driving in fog needs to be researched further to be able to interpret the influence of this effect.

465 This study has multiple limitations. The simulation of driving in a fixed based simulator, and
466 especially the simulation of fog is different from real life driving and reduced visibility in the
467 real-life driving environment. The inconclusive results of earlier studies on the influence of
468 fog on following distances (Broughton, Switzer, and Scott, 2007; Saffarian, Happee, De
469 Winter, 2012; Van der Hulst, Rothengatter, Meijman, 1998) could in part be attributed to
470 differences in the display of fog in driving simulators. The results therefore have to be
471 confirmed in real life driving conditions. Although the truck condition was introduced to
472 restrict the forward visibility of participants, the truck model differed from vehicle models in
473 the fog and clear condition due to its larger size. Vehicle size has been found to influence
474 following behaviour (Brackstone, Waterson, & McDonald, 2009; Duan, Li, & Salvendy, 2013;
475 Green & Yoo, 1999; Sayer, Mefford, & Huang, 2000). As such, effects found in the truck
476 condition cannot be solely attributed to the obstructed forward view, but could further be
477 influenced by the larger vehicle size. Future experiments should take this into account, e.g. by
478 using a lead vehicle model of normal size with opaque windows.

479 The highly automated vehicle that was simulated in this study was considerably simplified.
480 The car drove with a constant speed of 50, 100, or 150km/h, kept the lane perfectly, and never
481 overtook another vehicle. Future studies need to simulate highly automated vehicles that are
482 closer to their real life counterparts in their behavior. The exposure to highly automated
483 driving was very limited for most participants, it can be assumed that none of them had used a
484 highly automated vehicle in the past. It seems advisable to give participants more time to
485 familiarize themselves with the behavior of the simulated car as drivers need time to develop
486 a mental model of a car's automation (Beggiato, Pereira, Petzoldt, Krems, 2015). Apart from
487 little experience with highly automated driving, participants in this study were relatively
488 young, with a mean age of only 22.5 years, resulting in a relatively short driving experience.
489 Hence, future studies should aim to have a more representative sample.

490 In contrast to earlier studies on the topic of time headway and vehicle automation (Siebert et
491 al., 2014, 2017) there was no self-driving condition in this study, where the driver has
492 complete control over the vehicle. Implementing a self-driving condition in this study within
493 the experimental framework of comfort rated on a scaling lever would not have been possible,
494 since drivers need both hands to control the vehicle in self-driving, i.e. drivers cannot rate
495 their comfort through the lever while driving. Since it is unclear how comfort of time
496 headways in self- and highly automated driving relate to each other, future studies should
497 include a self-driving condition, even if it uses a different methodology for the collection of
498 comfort data. Further, despite earlier studies on the use of haptic rating devices (Charlton,
499 Starkey, Perrone, & Isler, 2014; Vehrs, 1986) for the subjective experience of study
500 participants, the novel use of a rating lever in traffic psychological experiments necessitates
501 the replication of our results with established methodological approaches. Despite these
502 limitations, this study provides a basis for the further investigation of additional variables that
503 influence following distances in highly automated driving.

504 In summary, the results of this study add to the existing literature on car following and are a
505 first step in expanding the field of research on car following from self-driving to highly
506 automated driving. Speed influenced the comfort ratings of time headways, a finding that
507 contrasts with results found in self and assisted driving. Reduced visibility led to a decrease in
508 comfort. Results indicate that time headways in highly automated driving will need to be
509 adaptively adjusted to speed and the road environment. Future studies need to investigate
510 these effects in real life driving, and investigate the influence of differences in visibility range
511 during fog in more detail.

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