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Empowering Driver-Passenger Collaboration: Designing In-Car Systems with a Focus on Social Connectedness, Fairness, and Team Performance

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ABSTRACT
Driving a car can be difficult when it comes to distractions caused by operating the in-vehicle infotainment system (IVIS). In-car passengers often help with performing IVIS-related tasks. However, an IVIS is often not designed with a focus on task collaboration. In this article, we focus on how to design in-car systems with the goal to support collaboration between a driver and a front-seat passenger. Based on infotainment-oriented tasks, we initially explore five key collaborative control concepts by means of an IVIS which differ from each other in terms of the number of available IVIS screens (one or two), access to menus (restricted and unrestricted), and the nature of performing tasks in parallel or one after the other. Results from a simulator study with $N = 16$ pairs show significant effects of the concepts on social collaboration in terms of perceived social connectedness (measured with sub-dimensions connectedness, affiliation, belongingness, companionship), team performance (coordination effectiveness and team cohesion), and fairness. We found that especially a dedicated passenger IVIS screen empowers front-seat passengers, reduces power dynamics, supports fairness, and minimizes driver distraction (caused by interacting passengers). We discuss the implications of these findings and posit recommendations to design future IVIS in passenger cars with improved driver-passenger collaboration by explicitly designing for balanced power roles, situational awareness, active communication, and a balance between drivers' privacy and trust toward the passenger. Additionally, we outline a systematic overview of future work to explore the research field of driver-passenger collaboration in more breadth and depth.

KEYWORDS
Social control; social connectedness; team performance; fairness; driver-passenger collaboration; in-vehicle infotainment systems; shared control

1. Introduction

The car is among the most important consumer goods of the 20th century. Especially through the technological developments in the past decades, the car became more than just a mode of transportation. Particularly the technological advancements of assisted driving and the increased need for enhanced in-car experience shape how we perceive a car ride today. Already two decades ago, car manufacturers introduced in-vehicle infotainment systems (IVIS) with the goal to increase entertainment and comfort during journeys (Kern & Schmidt, 2009). Nowadays, available IVIS functions range from navigation, and music, to messaging, e-mail, and internet services. However, the performance of so-called non-driving-related activities (NDRAs) by a driver, especially in highly dense traffic situations distracts and increases crash risk up to 4.6 times (Strayer et al., 2019). To counteract this, research proposes the design of collaborative in-car systems to enable passengers to take over certain NDRAs (Berger et al., 2021; Strayer et al., 2019). Thus, there is a need to understand from a user's experience side how to design for a seamless and enjoyable driving experience by supporting collaboration with the goal to lower driver distraction and increase safety.

When it comes to collaboration in the car, it is mainly the front-seat passenger who takes over certain tasks or parts of the task the driver is trying to accomplish. An example can be a shared car ride during the night when it is also heavily raining. Already the driving task itself causes a high cognitive workload for the driving task while in addition (s)he might be trying to find the nearest gas station by using the integrated navigation system. Especially in such a situation, the front-seat passenger can take over this task by accessing the integrated IVIS at the cars' center stack (see Figure 1), setting the gas station as the next destination while also extending turn-by-turn instructions. However, an integrated IVIS is still designed for primary use by the driver only. Some existing IVISs, for instance, are tilted towards the driver, and thus the content is not fully visible to the front-seat passenger, while the screen itself is also harder to reach. Therefore, Maurer et al. proposed to highlight front-seat passengers' gaze on the windshield to help

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Figure 1. In this paper, we investigate different approaches to driver-passenger collaboration by means of an IVIS. Based on an experimental evaluation, we outline design recommendations to best support collaboration in future cars. (Bootstrap icons).

drivers spot dangerous situations (Maurer et al., 2014). Other solutions focus on giving front-seat passengers better access to the IVIS by providing a split-screen user interface that shows content on the passenger side of the screen (e.g., BMW AG, 2001; Google.com, 2020; Perterer et al., 2013), enabling to delegate the IVIS screen and tasks towards the front-seat passengers' side (Berger et al., 2021; Perterer et al., 2013) or by simply placing an additional screen on the passengers' dashboard (e.g., Berger et al., 2019; BMW AG, 2017; Perterer et al., 2013; Porsche AG, 2019). Even when passengers' access to an IVIS is guaranteed, the likelihood of collaboration strongly depends on the social and personal context (Obrist et al., 2008) e.g., the relationship between drivers and passengers, the diversity in terms of gender, as well as on the maintained social interaction, and perceived social connectedness (Berger et al., 2021; Gridling et al., 2012). Especially direct communication enhances social interaction in the car (Fischer et al., 2014; Perterer et al., 2013). In addition, encouraging active participation (Koch & Gross, 2006; Marakas, 1998), supporting team performance (Paul et al., 2016), fairness, and enhancing social connectedness (Ammarapala & Luxhøj, 2007; Lee & Robbins, 1995) constitute towards a good group collaboration.

While previous research imposes the driver/passenger with additional car-related information (Berger et al., 2019; Maurer et al., 2014; Porsche AG, 2019; Turkus, 2019) or enables the passenger with better access to IVIS functionalities (Berger et al., 2021; BMW AG, 2001; Google.com, 2020), little is known about how to design for a higher level of social interaction to best support driver-passenger collaboration. To overcome this limitation, we see the need to investigate how different concepts of driver-passenger collaboration by means of an IVIS influence team performance, perceived social connectedness, and fairness. In this article, we focus on answering the following research question (RQ): *How does the design for in-car collaboration between a driver and a front-seat passenger affect and support team performance, social connectedness, and fairness?*

We designed five different types of IVIS concepts (*Consensual, Token-Ring, Hierarchical, Autocratic, and Anarchic control*; details see Section 3) to support driver-passenger collaboration in a manually driven car. To evaluate their effect on team performance, perceived social connectedness, and fairness, and to understand the concepts' impact on driving performance, we conducted a mixed-design experiment in a simulator with driver-passenger pairs ($N = 16$). Insights show that the single-display IVIS setup (*Autocratic control*) leads towards high belongingness, connectedness, and coordination effectiveness, while the majority of drivers feel distracted once a passenger interacts with the screen. Providing two IVIS screens (*Anarchic* or *Hierarchical control*) instead empowers front-seat passengers, reduces power dynamics, and minimizes driver distraction caused by interacting passengers.

In this work, we contribute to the understanding of the design of five collaborative IVIS concepts to enhance in-car collaboration between a driver and a front-seat passenger. Based on an empirical study in a driving simulator, we provide insights into how these concepts affect social connectedness and team performance. In this extended version of our AutomotiveUI '22 paper (Berger et al., 2022), we deepen the insights from that paper towards the social aspects of in-car collaboration by outlining the concepts' impact on fairness and report in addition on users' concept preferences. Based on these insights, we contribute a set of design recommendations to best support social connectedness, team performance, and fairness among a driver and a front-seat passenger while minimizing driver distraction and supporting perceived safety. We conclude by outlining a structural plan for future research to systematically explore additional, contextual dimensions (e.g., social, personal context) concerning driver-passenger collaboration.

2. Background and related work

To reduce driver distraction (Strayer et al., 2019) and improve in-car experience (Berger et al., 2021; Gridling et al., 2012), research proposes to design in-vehicle infotainment systems towards the support of driver-passenger collaboration. In the following, we first provide an overview of psychological aspects concerning social collaboration and outline how to design for co-located collaboration in general. We then look into existing concepts to support driver-passenger collaboration in manually driven cars and report on important contextual factors to consider, under which we conclude by outlining current research gaps and positioning our work.

2.1. Social aspects of co-located collaboration

Social interaction is natural, a basic human need, and also essential when working on goals together (Salvador, 1997). The successful collaboration on a specific goal in a group of co-located users gets strongly influenced by individuals' perception of team performance (Paul et al., 2016), fairness, and social connectedness (Ammarapala & Luxhøj, 2007; Lee & Robbins, 1995). Starting with team performance, Paul et.al. describes this as an interplay between coordination effectiveness and team cohesion (Paul et al., 2016). While coordination effectiveness is defined as the manifesting of a certain goal, team cohesion refers to the shared norms, values, and goals among individuals working together in a group (Paul et al., 2016). Social connectedness instead relates to the psychological construct of perceived belongingness, affiliation, companionship, and connectedness as an individual towards the group (Ammarapala & Luxhøj, 2007; Lee & Robbins, 1995). More precisely, it describes feelings related to how much a group member belongs to a group (Ammarapala & Luxhøj, 2007; Lee & Robbins, 1995). While particularly affiliation supports social interaction and helps to maintain a social bond (Wong & Csíkszentmihályi, 1991), a high level of companionship increases social satisfaction due to the support of well-being (Rook, 1987). In the event of successful collaboration, where high team performance and social connectedness should be maintained, fairness plays an essential role too (Uhde et al., 2020). Research outlines, that the perceived justice and promotion of individual rights can impact belongingness (O'Brien, 2011), which can in case of absence prevent teams from sharing norms that further impact collaboration, particularly team performance negatively (Uhde et al., 2020). Overall, team performance, social connectedness, and fairness can be maintained by supporting direct communication (Fischer et al., 2014) and social engagement (Liu et al, 2022). Previous research shows, that especially affiliation constitutes a higher social interaction and helps to establish self-esteem (Lee & Robbins, 1995) as well as a social bond between group members (Berger et al., 2022; Wong & Csíkszentmihályi, 1991). Additionally, a high level of companionship – maintaining fellowship – impacts social satisfaction positively because it supports well-being and reduces stress (Rook, 1987). Apart from that social interaction and collaboration get also impacted by the decision-makers involved – the presence of people who tend to decide for a whole group (Marakas, 1998; Neale et al., 2004). While also the time aspect of collaboration, whether collaboration happens together at the same time (synchronously) or one after another (asynchronously) (Grudin, 1994) has an influence on the group outcome. Marakas (Marakas, 1998) defines three major types of decision-makers in a social setting: *Multiple decision makers*, where group members do not have equal authority in making decisions, but none of them have enough authority to make all decisions alone. *Group decision makers* are defined as each group member having equal weight in making decisions. The *team decision makers* is characterized by an individual decision-maker who has the authority to make final decisions under negotiated outcome. In contrast to group decision-makers, there is the situation of *individual decision makers*, where every group member decides alone under the focus on achieving a common goal without group negotiation (Ammarapala & Luxhøj, 2007). Besides, research highlights, that group members become less satisfied and also less productive the more people are in a group (Isaac & Walker, 1988; Salomon & Globerson, 1989), notably with a group of six or more members (Ammarapala & Luxhøj, 2007; Salomon & Globerson, 1989). With many people involved, the decision possibilities of individuals are also limited and not always equally distributed. This can violate fairness, and induce power dynamics, and hierarchies which let users tend to feel excluded with a high chance to cause conflicts (Dourish & Bellotti, 1992) and vandalism (Kittur et al., 2007).

2.2. Design of multi-user interactive systems for co-located users

To support social interaction among co-located users mediated through technology with the goal to enhance social satisfaction, it is important to smoothly facilitate and balance decision-makers and individuals' level of control authority (Marakas, 1998; Neale et al., 2004). This can be achieved by applying coordination policies (Marakas, 1998; Morris et al., 2004) which are about introducing (a) a voting system for *multiple decision makers* (Marakas, 1998; Morris et al., 2004), where group members can only jointly make a decision. Additional concepts refer to (b) having a key-user who decides on behalf of the group (Marakas, 1998; Morris et al., 2004), letting everyone decide individually (Ammarapala & Luxhøj, 2007; Morris et al., 2004), (c) providing users with different control/access levels (Flemisch et al., 2012; Marakas, 1998; Morris et al., 2004), or (d) assigning dedicated functions to specific users (Marakas, 1998; Morris et al., 2004).

Previous work on interactive, collaborative system design reports that a democratic selection of content supports fairness (Plaumann et al., 2016), is entertaining (Berger et al., 2022; Plaumann et al., 2016), and increases the social value and interaction (O'Hara et al., 2004). Additionally, it generates a high feeling of belongingness and affiliation among group members (Berger et al., 2022). However, it is time-consuming (Berger et al., 2022) and the execution of frequently used tasks can be tedious (Plaumann et al., 2016). Based on the use-case of controlling a TV, Plaumann et al. report that the key user approach avoids conflicts and prevents also technical problems during simultaneous interactions (Plaumann et al., 2016). Even though the key user approach is familiar to users, and perceived as more efficient, it tends to pull users apart due to restricted control possibilities which induce a lack of individual contribution towards the group goal (Berger et al., 2022). While providing different access levels, restricting menu access depending on users' abilities (Flemisch et al., 2012), appears promising in involving every group member actively (Morris et al., 2004), users fear strengthening power games which might increase the potential of interpersonal conflicts (Berger et al., 2022; Plaumann et al., 2016). Overall, multi-user interactive, collaborative systems should prevent the accidental execution of tasks (Morris et al., 2006), while still supporting inclusion and fairness (Berger et al., 2022). In addition, it needs to be carefully decided whether a task is suitable to be performed collaboratively Morris et al. (2006). Moreover, enhancing change awareness while collaborating by highlighting someone's contribution and making interactions visible in real time supports effectiveness (Gutwin &

Greenberg, 2002; Tam & Greenberg, 2006; Yuill & Roger, 2012) and social interaction (Cesar & Geerts, 2017).

2.3. Driver-passenger collaboration in manually driven cars

Collaboration between a driver and a passenger in manually driven cars is established for decades. Passengers' main support towards the driver refers to providing turn-by-turn instructions or performing certain non-driving-related activities (NDRAs) (e.g., entertainment, communication, etc.). Since passengers can process and review more and also detailed information, a viable approach to driver-passenger collaboration lies in providing the front-seat passenger with more details about the route and the destination, compared to what a standard navigation system offers (e.g., opening hours of buildings) (Antrobus et al., 2017; Meschtscherjakov et al., 2017; Perterer et al., 2015). Such details can then be verbally shared with the driver (Meschtscherjakov et al., 2017) which prevents navigation errors, and visual distraction, and, in addition, enhances the chance of remembering the route (Antrobus et al., 2017). While gaining more information about the route can be easily achieved nowadays with a smartphone, prior research outlines that passengers wish for assisting with a broad range of in-car related activities (Berger et al., 2021; Inbar & Tractinsky, 2011). Berger et al. report, that passengers strive for having shared access to all in-car functions and be able to better control an in-vehicle infotainment system (IVIS) (Berger et al., 2021). Designing with this in mind enables the passenger to become a co-driver which reduces driver distraction and enhances passenger experience (Berger et al., 2021). However, most cars today are equipped with a single IVIS only, dedicated for use by the driver. To enhance collaboration by means of a single IVIS, Berger et al. introduced a moving IVIS screen (Berger et al., 2021) to provide the front-seat passenger with better access to functions. The driver can delegate the IVIS screen to the passenger to receive dedicated support while not being distracted by the passenger performing NDRAs. Other concepts target user interfaces that demonstrate passenger-relevant functions on the passenger side of the IVIS screen (e.g., BMW AG, 2001; Google, 2020; Perterer et al., 2013). It allows easier access for the front-seat passenger, while the driver is still able also to use the functions. Additionally, both research and industry focused on simply placing another screen in front of the passenger to support in-car collaboration (e.g., Berger et al., 2019; BMW AG, 2001; Perterer et al., 2013; Porsche AG, 2019). This approach, on the one hand, enhances the passenger experience, while on the other hand stimulates discussion and enhances social connectedness (Berger et al., 2019). In a recent study, Berger et al. showed that applying the above-outlined coordination policies to design different ways of driver-passenger collaboration by means of an IVIS, has an influence on perceived social connectedness as well as team performance (Berger et al., 2022). Particularly, providing the driver and the passenger with a dedicated screen and unlimited access to IVIS promotes coordination effectiveness while lowering driver distraction (Berger et al., 2022). Apart from providing passengers with access to IVIS functions, research outlines that the act of sharing information with the driver supports social engagement (Meschtscherjakov et al., 2016), enhances in-car experience (Berger et al., 2019) and lets passengers feel that they belong and contribute towards a positive atmosphere (Berger et al., 2022). Possible use-cases of information sharing can be enabling the passenger to propose intermediate stops, which can then be accepted/declined by the driver (BMW AG, 2017). However, drivers receiving so-called push notifications on an IVIS screen increase driver distraction and has a negative impact on driving performance (Berger et al., 2022).

Taken together, research outlines that maintaining social aspects, particularly individuals' perceived team performance, social connectedness, and fairness are important for successful group collaboration. Since applying different coordination policies (Morris et al., 2004) in a non-automotive related context shows the ability to enhance social interaction, we see the potential to investigate how these policies can be applied in the car to support social interaction among a driver and a front-seat passenger when collaborating by means of an IVIS.

2.4. Contextual dimensions to consider when supporting collaboration in the car

Besides the social aspects discussed above (team performance, social connectedness, fairness) concerning collaboration, the general type and amount of support differ depending on the driving situation/context (Gridling et al., 2012). The most prominent example refers to the so-called ***social context*** – in company or alone and to "the social structure" (Obrist et al., 2008) among occupants. This can on the one hand be attributed to the relationship between a driver and a passenger (e.g., family, friends, work colleagues, strangers), while also to diverse age groups (e.g., elderly, children, adults) (Gridling et al., 2012; Obrist et al., 2008). Gridling et al. outline that the barrier towards driver support among strangers in the car or in the context of a paid service (e.g., taxi) is quite high, while support among friends or family members happens frequently (Gridling et al., 2012). Additionally, the ***personal context*** (Obrist et al., 2008) can have an influence due to occupants' diversity in terms of gender, technological know-how, disabilities, and/or special needs (Berger et al., 2021; Obrist et al., 2008). While also the ***context of the context*** (Obrist et al., 2008), which refers to cultural backgrounds, norms, and nations can have an influence on whether and how collaboration gets performed. A big role plays the ***technological context*** in the car which can be attributed to the equipment, devices (both integrated or brought in), or services provided (Berger et al., 2021). Among these factors, literature also talks about the ***spatial context*** (Obrist et al., 2008), referring to collaboration with people inside (co-located) or outside the car (not co-located) and the ***temporal context*** (Obrist et al., 2008) which is about the duration, and point in time of the collaboration (e.g., day/night, summer/winter). We frame the design of the collaborative IVIS concepts (Section 3) and the experimental set-up (Section 5.1) under the lens of these contextual dimensions.

3. Social Control: Design for Driver-Passenger Collaboration

With our design of collaborative in-car systems, we aim for the support of social interaction to enhance driver-passenger collaboration in current cars. To structurally explore this topic, our initial focus lies on the conventional context of collaboration between a driver and a front-seat passenger by means of an in-vehicle-infotainment system (IVIS). Thus, the contextual dimensions considered at the design stage are the *spatial context* of co-located collaboration in a car between a driver and a front-seat passenger, the *social context* of two collaborating together on a goal, and the *technological context* of supporting the collaboration by means of an IVIS.

3.1. Design of five collaborative IVIS approaches

Prior work shows that applying different coordination policies enriches collaboration (Morris et al., 2004; Neale et al., 2004) as well as social interaction (Berger et al., 2022). We, therefore, extended their design by applying these policies to our use case of driver-passenger collaboration. Additionally, prior research highlights that co-located collaborative systems should balance decision-makers in order to avoid conflicts (Ammarapala & Luxhøj, 2007; Grudin, 1994; Marakas, 1998; Morris et al., 2004; Plaumann et al., 2016). Moreover, collaboration can happen time-synchronously as well as asynchronously (Grudin, 1994) by means of an IVIS screen. Additionally, full access or restricted access to menus/information can influence team performance (Flemisch et al., 2012; Neale et al., 2004). Overall, co-located collaborative systems should support users in *being aware of other group-members' activities* (Cesar & Geerts, 2017; Gutwin & Greenberg, 2002), *encouraging communication* (Cesar & Geerts, 2017; Fischer et al., 2014), and *supporting real-time interaction* (Cesar & Geerts, 2017). Under these aspects, we designed five collaborative IVIS concepts (see Table 1) which implement shared access to menus. We derived the concepts from prior work concerning multi-user interactive system design (e.g., Berger et al., 2022; Flemisch et al., 2012; Grudin, 1994; Morris et al., 2004; Neale et al., 2004; Plaumann et al., 2016), social aspects of group collaboration (Ammarapala & Luxhøj, 2007; Marakas, 1998) in combination with existing collaborative in-car systems (Berger et al., 2021; BMW AG, 2001, 2017; Turkus, 2019).

For the general design of the IVIS user interface (UI) (see Figure 2a), we took existing in-car UIs such as *BMW iDrive*, *Apple CarPlay* and *Android Auto* as inspiration and integrated access to standard in-car functions such as navigation, radio, music (collaborative functions), phone, messaging, calendar, settings (personalized functions) and car status (informative function). The individual concepts and their corresponding UI designs are explained below.

The Anarchic Control Concept is about individual decision makers (Ammarapala & Luxhøj, 2007) who control anything synchronously (Grudin, 1994) and at any time (Morris et al., 2004). Thus, the driver and the front-seat passenger can make control decisions, which can affect decisions made by the other user since the last action always overrules all precedent actions. To enable anarchic control, the driver and the passenger are equipped with individual IVIS screens, similar to Porsche's passenger screen (Turkus, 2019) while providing unrestricted access to IVIS menus (see Figure 2a).

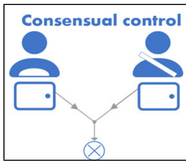
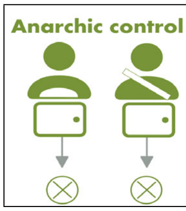
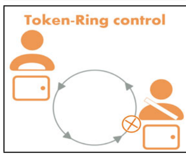
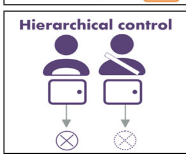
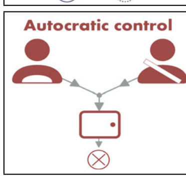
The Consensual Control Concept employs the idea of joint decision making (Marakas, 1998) which incorporates democratic decision making such as voting for changes (Morris et al., 2004; Plaumann et al., 2016). The driver and the front-seat passenger have unrestricted access to IVIS menus with their individual screen. However, a control decision (e.g., changing the radio channel, adding an intermediate stop) can only be made when both agree on an action to be performed. Whenever there is a control decision to be agreed on, the UI displays a pop-up notification for accepting or declining the decision (Figure 2d), similar to BMW's concept of sending requests to the driver via the rear-seat IVIS (BMW AG, 2017). The notification occurs on the drivers' screen for passenger decisions, and on the passengers' for driver decisions. Thus, only those decisions get executed that want to be executed by both, while no one can control functions individually.

The Token-Ring Control Concept employs individual decision makers (Ammarapala & Luxhøj, 2007) who collaborate time asynchronously (Grudin, 1994) by having an individual screen. It uses a virtual token that moves between the driver and the front-seat passenger and takes away access to menus from the driver (e.g., during dense traffic) and instead provides the passenger with additional access. For the sake of our experiment, the token movement bases on wizard-of-oz, providing full menu access to the token holder (Figure 2a) and limited access (no access to the collaborative menus such as navigation, radio, and music) to the user without the token (Figure 2b).

The Hierarchical Control Concept provides the driver and the front-seat passenger with individual screens and interfaces, with the driver having full menu access (Figure 2a) and the passenger having limited access (Figure 2c). Thus, this concept employs different levels of menu access (Flemisch et al., 2012; Neale et al., 2004) and control possibilities (Plaumann et al., 2016). Overall, the concept is meant that the driver can decide prior to a journey on which IVIS menu the front-seat passenger can provide assistance. For our investigation of this concept, we pre-assigned the menu function; radio, and music to the passenger which means, the passenger had restricted menu access. However, it was still possible for the passenger to reach the driver's screen if necessary.

The Autocratic Control Concept constitutes a single IVIS screen (Figure 2a), placed in the middle of the car's

Table 1. Overview of the main design characteristics of each collaborative IVIS to demonstrate how the concepts differ from each other.

Concept	Characteristics										
	IVIS screens			time-based[1]		menu access[2]			decision making[3]		
Illustration	one IVIS	two IVIS	shared driver IVIS	synchronous	asynchronous	unrestricted	driver restricted	passenger restricted	together/jointly	individual	single
		✓		✓		✓			✓		
		✓		✓		✓				✓	
		✓			✓		✓	✓		✓	
		✓	✓	✓				✓		✓	
	✓		✓		✓			✓			✓

[1]Grudin, 1994, [2]Flemisch et al., 2012; Neale et al., 2004, [3]Ammarapala & Luxhøj, 2007; Marakas, 1998 (Bootstrap icons).

dashboard which reflects the current center console in cars. This concept refers to having a single key-user (Marakas, 1998; Plaumann et al., 2016) where the driver can dictate control while the front-seat passenger can only interact once the driver explicitly allows or requests for it. Thus, there is only one user able to physically access the IVIS screen at a certain time which reflects asynchronous collaboration by sharing a single IVIS screen. While one user interacts with the IVIS, the other group member relies on those made decisions (Flemisch et al., 2012; Neale et al., 2004). We integrated this "conventional" setup as a baseline to compare this established interaction paradigm with the more novel ones outlined above.

4. Research question and hypotheses

Decision-making and collaboration among co-located users get influenced by individuals' perceived social connectedness (Ammarapala & Luxhøj, 2007; Berger et al., 2022; Lee & Robbins, 1995; Rook, 1987), fairness (O'Brien, 2011; Uhde et al., 2020), and the overall team performance (Berger et al., 2022; Paul et al., 2016). Thus, we see these factors as an indicator of effective collaboration in the car. To explore how the collaborative IVIS concepts support driver-passenger collaboration we ask: *How do the collaborative IVIS concepts differ in the evoked social connectedness, fairness, and team performance when a driver and a front-seat passenger collaborate on a task while riding in a standard car?* Thus, we want to explore whether there is a difference in the perceived social connectedness (H1), team performance (H2), and fairness (H3) depending on the type of collaborative concept.

H1. The type of collaborative IVIS has an effect on driver's/passenger's perceived social connectedness in terms of belongingness, affiliation, connectedness, and companionship

H2. The type of collaborative IVIS has an effect on driver's/passenger's perceived team performance in terms of coordination effectiveness and team cohesion

H3. The type of collaborative IVIS has an effect on driver's/passenger's perceived fairness

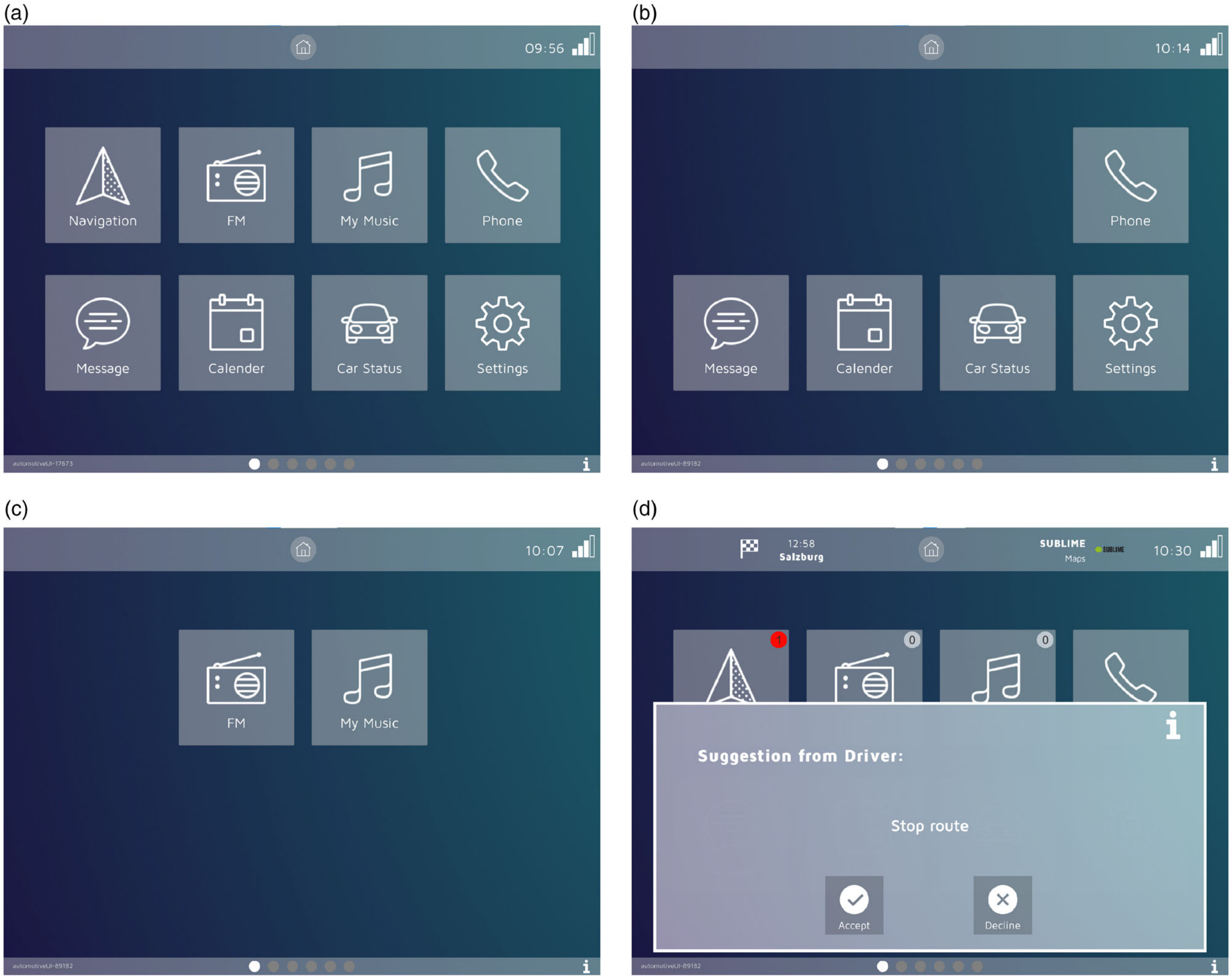


Figure 2. Representation of the UI of the individual IVIS concepts. (icons by Icons8.com). (a) Standard IVIS home screen with full access to all menus. (b) Token-less home screen under *Token-Ring control*. Navigation and music menus not available. (c) Passenger home screen of *Hierarchical control*. Only music menus are available. (d) Pop-up notification under *Consensual control* to accept/decline decisions from another user.

5. Comparative study of the five collaborative IVIS concepts

We conducted an exploratory, mixed-design experiment in a driving simulator with pairs of driver and front-seat passengers (see Figure 3) to study the five concepts' effect on social connectedness, team performance, and fairness.

5.1. Method choice

The goal of this study thus is to research how the five IVIS concepts affect social collaboration and to understand how the design characteristics (outlined in Table 1; single vs. double IVIS, time-based collaboration, access to menus, decision making) support or hinder driver-passenger collaboration. For this initial, empirical investigation of the concepts, we considered the contextual factors (Section 2.4), of the *temporal context* related to collaboration while driving during the day, by light, the *social context* of driver-passenger pairs that know each other to balance for influence that can come from working with strangers (Gridling et al., 2012), the *personal context* of users having experience with using touch-screen-based devices and the *context of the context* related to Mid-Europe (due to the location of our research institution). Concerning the method in general, a study on in-car interaction should be idealistically performed in the most realistic driving environment. This means, observing drivers and passengers on how they interact with the five designed IVIS systems in today's most recent cars in a real driving scenario ensures ecological validity. However, it poses a risk to participants and is therefore ethically not justifiable. Additionally, real-life driving scenarios cannot be controlled and thus do not equal among conditions which limits comparability of the insights among concepts (Carsten & Jamson, 2011). Due to these influencing factors, a real-world study requires more time and is described as less efficient and effective compared to a simulator study (Carsten & Jamson, 2011). To ensure the safety of the participants and to balance the need to study the set of five collaborative IVIS concepts under controlled conditions, we decided to perform the study in a driving simulator. Even though insights from a simulated environment are limited in terms of realism, since participants are aware that risky driving styles (e.g., near) accidents) do not have consequences, we argue that a driving simulator is an ecologically valid approach to initially investigate the concepts' effect on social collaboration. A main advantage of the simulator lies in the creation of repeatable situations, driving scenes, and scenarios which enables to control external influencing factors (Carsten & Jamson, 2011). This allows drawing overall conclusions by comparing the concepts with one another in an efficient and effective way (Carsten & Jamson, 2011). Overall, simulated driving enables participants to feel and experience the impact that the different concepts have in terms of collaborative support and their influence on safe driving.

5.2. Study set-up

Within the driving simulator (see Figure 3), we conducted a mixed-design experiment.

5.2.1. Independent variables

As independent variables, we had the five collaborative IVIS concepts as the within-subject variable (*Consensual, Token-Ring, Hierarchical, Autocratic, and Anarchic control*) and the sitting position/role as the between-subject variable (driver, front-seat passenger).

5.2.2. Dependent variables/measurements

We measured driver's and passenger's perceived social connectedness in terms of connectedness, companionship, and group affiliation using the Social Connectedness Scale (Lee & Robbins, 1995) and group belongingness by means of the Inclusion of Community in Self-Scale (Mashek et al, 2007). To assess team performance in terms of coordination effectiveness and team cohesion, we applied the team performance questionnaire by Paul et al. (Paul et al., 2016) (three questions each). In addition, we assessed the perceived fairness by self-defined questions (Q1: I had the feeling that others had more operating options than I had; Q2: I think the distribution of the operating options among the group members was fair) based on a 5-point Likert scale (fully agree to do not agree at all). An overview of the questions per questionnaire can be found in Appendix A. We used participants' qualitative feedback to determine the positive and negative characteristics of the different concepts under investigation. In addition, we used subjective ranking to investigate users' preferences among the five concepts.

Figure 3. Demonstration of the simulator and study set-up with the mounted IVIS screens.

To control for possible influences due to driver distraction, we assessed the driving performance by measuring average speed [km/h] (Van Winsum & Godthelp, 1996) and the standard deviation of the lane position (SDLP) [m] (Green, 2013). Concerning driver distraction, we measured the *eyes-off-the-road time* Ghazizadeh et al. (2013) with SMI eye-tracking glasses. This means the drivers' eyes-off-the-road time refers to the percentage of time that the driver's gaze was not focused on the road while a task was performed, either by the driver or the passenger. We calculated the driver's eye-off-the-road time for each task performed, whether by the driver themselves, or the passenger. The total eye-off-the-road time for the driver tasks was calculated as an aggregate of eyes-off-the-road time across all four driver tasks (i.e., the sum of four tasks, excluding the audio instructions prior to the task). Similarly, the total eye-off-the-road time for the passenger tasks was calculated as an aggregate of eyes-off-the-road time across all the four passenger tasks.

5.3. Participants

We recruited participants within the university through e-mail invitations. For every recruited pair, one needed to have a valid driver's license. Overall, the experiment sample consisted of 16 driver-passenger pairs (a total of 32 participants, 7 same-gender pairs and 9 mixed-gender pairs), 13 male and 19 female, living in the Netherlands. Three pairs reported not knowing each other, while the remaining had either a friendship (6 pairs) or a working relationship (7 pairs). Their age ranged from 21 to 46 ($M = 28.12$years, $SD = 4.3$years). In addition, 26 out of 32 participants reported on prior experiences with an IVIS. All participants used touchscreen-based devices several times a week.

5.4. Apparatus

We implemented the driver/passenger IVIS UI (Figure 2a) for a 12-inch tablet screen with a resolution of 2048×1536 using *Unity 3D*[1]. To exchange information among IVIS screens in real-time, we used the Message Queuing Telemetry Transport (MQTT) protocol[2]. To simulate the driving experience, we set up a manually driven left-hand drive car simulator with automatic gear shift and real car seats (see Figure 3). We mounted a wooden dashboard, steering wheel, and instrument cluster on a height-adjustable table that we moved to the lowest possible position to mimic the interior and demonstrate a realistic in-car experience. The dashboard size matched the standard C-segment car and had slots to mount the IVIS screens for the driver and the passenger. Another 12-inch screen was used as an instrument cluster and placed behind the steering wheel. As steering wheel and pedals we used the *Logitech G25* gaming console. The overall driving scene was projected onto the wall in front of the simulator and a driving-related audio scenery was provided via speakers placed behind the dashboard (not visible to participants). The simulator software represented a two-lane fairly-lean highway with traffic only on the right lane. Furthermore, the driving scene referred to a sunny drive in daylight without weather disturbances. The overall simulator was set up in an empty, dim-light lab.

5.5. Procedure

First, we introduced the overall study goal and asked participants for their informed consent. After, we assigned the pair of participants to the driver or the passenger role and let them individually answer demographic questions (Figure 4). Once both took a seat in the simulator, we introduced the driver to the driving rules: driving on the left lane of a two-lane highway, maintaining a constant speed of 80 km/h, speeding was forbidden and there was no other traffic on the left lane (traffic appeared only on the right).

To assess the IVIS concepts' impact on collaboration, we aimed for a controlled social situation in the car. Since we wanted to understand the collaborative nature rather than the level of self-explanatory, we orally introduced each concept and let the concept re-explain by participants to ensure every participant had the same knowledge about the concept. We also introduced the participants to a social, collaborative scenario of going on vacation, driving from Eindhoven to another city in Europe (Salzburg, Amsterdam, Utrecht, Rotterdam, Groningen). To make the ride as comfortable as possible, the driver and passenger had to collaborate and assist each other while operating the IVIS. We introduced the social scenario and the tasks by handing out cards prior to each concept test round. The task card contained the scenario description and a total set of eight tasks (4 driver tasks, 4 passenger tasks). The tasks were similar among the concepts, only the destinations and items (e.g., song or radio channel) changed to avoid boredom and minimize learning effects. To avoid a high mental demand and a wrong task order, the participants were not asked to remember the tasks and recall them from memory; instead, we gave short audio instructions during the ride. Therefore, each task got introduced with" Hey driver" or" Hey passenger" followed by the task instruction which lasted between 4 and 8 s.

The experiment started with a trial round to familiarize the participants with the driving simulator, the IVIS UI, and the procedure of the task-cards along with the audio of task descriptions (Figure 4). This was followed by a fully counterbalanced set of the five IVIS concepts. For each concept, each participant had to perform four tasks (delegating all tasks to the passenger was not allowed). Table 2 presents the tasks and scenarios. Concerning the order, it was always the driver starting with task 1, followed by passenger task 1, and continued in alternating order. At the end of each concept condition, the participants filled out the questionnaires related to social connectedness, team performance, and fairness. In addition, the researchers asked about participants' positive and negative impressions after each concept. The

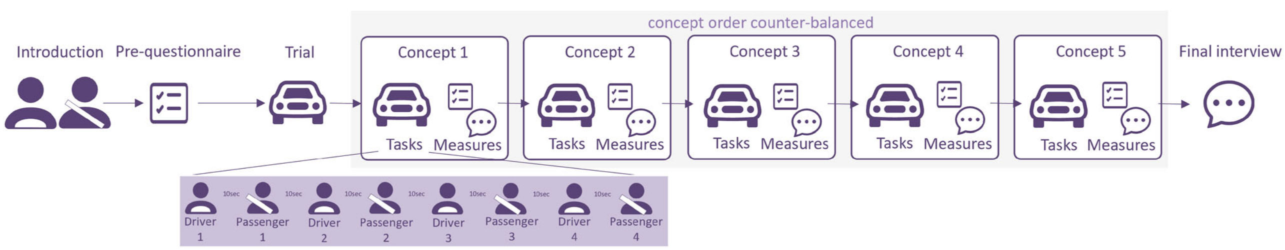


Figure 4. Visual demonstration of the study procedure in the driving simulator. After the trial, the sequence of the concepts was counterbalanced. (Bootstrap icons)

Table 2. Experimental tasks for driver and passenger.

Order	Task	Scenario description	Task description and audio instruction
1	Driver 1	You want to visit [Amsterdam / Rotterdam / Utrecht / Groningen / Salzburg] together.	Start the route to [Amsterdam/Rotterdam/Utrecht/Groningen/Salzburg] city.
2	Passenger 1	Since you are into museums/national parks, you also want to visit the [Rijksmuseum/Kinderdijk/St John's cathedral/Sallandse Heuvelrug/Lake Chiemsee].	Add the point of interest [Rijksmuseum/Kinderdijk/St John's cathedral/Sallandse Heuvelrug/Lake Chiemsee] to the route.
3	Driver 2	While driving to the museum/national park you want to get entertained. Therefore, you want to listen to the radio.	Start listening to radio channel [SUBLIME/SKY/NPO Radio 3/Slam/QMusic]
4	Passenger 2	You like to listen to music while riding. However, you are not satisfied with the current radio channel.	Change the radio channel to [QMusic/FunX/Sky/NPO Radio 1/SUBLIME]
5	Driver 3	You are also not satisfied with the music. So you decide to select a song from your own music library.	Go to my Music and select the song [Bang Bang/Get Lucky/A little Party/Sing/Crazy In Love] by [Jay-Z/Daft Punk/Jay-Z/Ed-Sheeran/Jay-Z]
6	Passenger 3	You also want to listen to one of your favourite songs.	Go to my music and add the song [Beyond/Touch/Lose Yourself/Kill and Run/ Don't] by [Daft Punk/Daft Punk/Daft Punk/Jay-Z/Ed Sheeran]
7	Driver 4	You decided to change your plans because you want to go for lunch first. This is why you want to cancel the current route.	Cancel the current route
8	Passenger 4	You are in charge of selecting the restaurant.	Start the route to the restaurant [Dutch/Shell/Beach/Italian/Burger place].

Destinations/items (stated in brackets) changed according to the concept to avoid boredom and reduce learnability effects [Anarchic/Autocratic/Hierarchical/Token-Ring/Consensual].

experiment concluded with a subjective ranking of all five concepts and a semi-structured interview about what they liked/disliked.

The experiment lasted on average 1.25 h, with 6 min spent on each concept. The participants did not receive compensation. Since the experiment took place during the COVID-19 pandemic, we followed the most recent regulations of the university (FFP2 masks were obligatory, a vaccination certificate was required, and all devices were sanitized after each group).

6. Results

6.1. Data analysis

We assessed the Likert Scale data for social connectedness (Lee & Robbins, 1995; Mashek et al, 2007), team performance (Paul et al., 2016), and fairness across the different IVIS concepts using Friedman tests. For the post-hoc pairwise comparisons, we performed Bonferroni-corrected Wilcoxon signed-rank tests. Due to the exploratory nature rather than conclusive nature of our study, we decided to partly report also on non-Bonferroni corrected pairwise comparisons (Armstrong, 2014). Since this is to our knowledge the first study assessing the social aspects of in-car collaboration, it allows to explore the concepts in more depth and provides more opportunities for future research (Armstrong, 2014). To investigate the impact of being a driver or a passenger (independent between-subject variable) and the impact of gender (same-gender pairs vs. mixed-gender pairs) on social connectedness, team performance, and fairness, we performed Mann–Whitney U tests. To determine whether the nature of collaboration impacts the driver negatively, we assess the effect of the concepts on driving performance (speed and SDLP) by conducting one-way repeated measures ANOVA. To investigate the level of drivers' distraction (eyes-off-the-road time), we conducted a Friedman test due to non-normality of the data. For better readability, we show the statistical test results in diagrams only.

6.2. Social connectedness

6.2.1. Group belongingness

A Friedman test shows that the effect of the IVIS concepts on users' perceived group belongingness is statistically significant (Figure 5). Bonferroni-corrected post-hoc tests show that *Autocratic control* results in statistically significantly higher group belongingness than *Anarchic control* and *Token-Ring control*. Further, as highlighted in Figure 5, the mean group belongingness score is average for *Consensual control* concept ($Mdn = d$), *Autocratic control* ($Mdn = d$), and *Hierarchical control* ($Mdn = d$), while the *Anarchic control* ($Mdn = c$) and *Token-ring control* ($Mdn = c$) scored below average. Additional pairwise comparisons outline higher group belongingness for *Autocratic control* than *Consensual control* and *Hierarchical control* compared to *Token-Ring control*. In summary, there is evidence that *Autocratic control* let users belong significantly better in comparison to *Anarchic control* and *Token-Ring control*.

6.2.2. Companionship

A Friedman test reports no significant effect of the concepts on the perceived companionship (see Figure 6). The median evoked companionship score is slightly above average for all concepts, with the lowest score for *Anarchic control*.

6.2.3. Connectedness

As Figure 7 shows, the effect of the IVIS concepts on evoked connectedness is statistically significant. While Bonferroni-corrected post-hoc tests do not show any significant differences, there is a tendency of a higher connectedness for *Autocratic control* compared to *Token-Ring control*, as

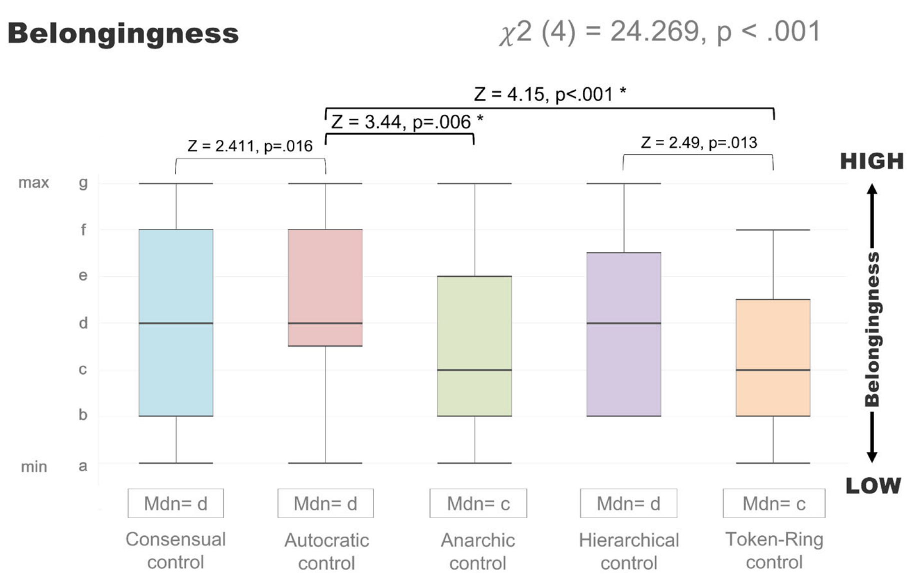


Figure 5. Belongingness measurements (Mashek et al, 2007) across the different collaborative IVIS concepts with pairwise comparisons. The scale ranges from a = low/min belongingness to g = high/max belongingness. Friedman test significant at $p < 0.05$. Bonferroni-corrected ($\alpha = 0.005$) Wilcoxon signed-rank post-hoc tests marked with *.

outlined by uncorrected pairwise comparisons. In addition, the median scores are above average for all the concepts, with the highest score for *Consensual control* ($Mdn = 5.25$) and *Hierarchical control* ($Mdn = 5.25$), followed by *Autocratic control* ($Mdn = 5.12$), *Anarchic control* ($Mdn = 5$), and *Token-Ring control* ($Mdn = 4.87$).

6.2.4. Affiliation

The Friedman test does not indicate a statistically significant effect of the different concepts on users' perceived affiliation (Figure 8). Nevertheless, the data shows a mean evoked affiliation above average for all concepts, with the highest affiliation for *Hierarchical control* ($Mdn = 5.17$).

6.3. Team performance

6.3.1. Coordination effectiveness

As shown in Figure 9, the effect of the IVIS concepts on users' perceived coordination effectiveness is statistically significant. Bonferroni-corrected post-hoc tests show that the *Autocratic control* concept results in statistically higher effectiveness compared to *Token-Ring control*. Further, the average coordination effectiveness is best for *Autocratic control* ($Mdn = 2.50$), followed by *Anarchic control* ($Mdn = 2.84$), *Hierarchical control* ($Mdn = 3$), *Token-Ring control* ($Mdn = 3.33$), and *Consensual control* ($Mdn = 3.33$). Pairwise comparison outlines that *Consensual control* leads towards lower coordination effectiveness compared to *Autocratic control*, *Anarchic control*, and *Hierarchical control*. Moreover, *Token-Ring control* evokes lower coordination effectiveness compared to *Anarchic control* and *Hierarchical control*. In summary, our results indicate that *Autocratic control* leads towards best coordination effectiveness, especially in comparison to *Token-Ring control*. Furthermore, *Consensual control* and *Token-Ring control* show the lowest coordination effectiveness among the concepts, while still scoring above average.

6.3.2. Team cohesion

The data outline no significant effect of the IVIS concepts on the perceived team cohesion. As shown in Figure 10, all concepts evoke a high team cohesion with the highest median scores for *Autocratic control* and *Anarchic control*.

6.4. Fairness

6.4.1. Perception of fairness support

There is a statistically significant effect of the concepts on perceived fairness ($\chi_2(4) = 20.693, p < 0.001$), as shown in Figure 11. Bonferroni-corrected post-hoc tests show that *Autocratic control* ($Z = -3.123, p = 0.018$) and *Anarchic control* ($Z = -3.162, p = 0.016$) result in statistically significantly higher fairness than *Hierarchical control*. Thus, our results indicate a direction towards *Hierarchical control* to be perceived as most unfair.

6.4.2. Perception of different control possibilities

A Friedman test outlines no significant effect of the different IVIS concepts on the perception of different control possibilities among the driver and the passenger ($\chi_2(4) = 5.76, p = 0.218$). Thus, our results indicate that users do not perceive differences in terms of control possibilities.

6.5. Effect of the driver/passenger role, gender pairs, and relationship status

We conducted Mann–Whitney U tests to determine whether there are differences in evoked social connectedness and team performance of the IVIS concepts between the driver and a passenger. The median scores do not show significant differences between driver and passenger for any of the concepts for either social connectedness, team performance, or fairness. Similarly, the test results do not show a statistically significant difference between same-gender pairs and mixed-gender pairs, indicating no evidence of gender pairs affecting the perceived social connectedness, team performance, or fairness. Moreover, there was also no significant difference observed between those driver-passenger pairs having a working relationship compared to the pairs indicating a friendship. This means, there is also no evidence of the relationship affecting the perceived social connectedness, team performance, or fairness.

6.6. Influences on driving performance & driver distraction

6.6.1. Driving performance

A one-way repeated measures ANOVA revealed (sphericity had not been violated as assessed by Mauchly's test – $\chi^2(9) = 10.24$, $p = 0.337$), that there is a statistically significant effect of the IVIS concepts on speed, $F(4, 48) = 3.21$, $p = 0.020$, $\eta^2 = .211$. However, Bonferroni-corrected post-hoc tests did not unveil statistically significant differences. Besides, there is no statistically significant effect of the IVIS concepts on SDLP, as assessed by an ANOVA, $F(1.23, 14.76) = 2.3$, $p = 0.148, \eta^2 = 0.161$ (sphericity has been violated for SDLP, as assessed by Mauchly's test - $\chi^2(9) = 55.645, p < 0.001$; thus a Greenhouse-Geisser correction was applied: $\varepsilon = 0.308$).

6.6.2. Driver distraction (eye tracking data)

A Friedman test does not show a significant effect of the IVIS concepts on drivers' eyes-off-the-road time ($\chi^2(4) = 6.057$, $p = 0.195$) on driver task execution. However, there is a significant effect on drivers' eyes-off-the-road time when the passenger performs tasks, $\chi^2(4) = 11.657$, $p = 0.020$. Post hoc-tests unveil that the time looked away from the road is statistically higher when using *Consensual control* compared to *Autocratic control*, $Z = 3.043$, $p = 0.002$. Overall, the *Consensual control* evokes the highest eyes-off-the road ratio ($M = 31.56\%$, $SD = 7.02\%$) when the driver performs tasks, followed by *Autocratic control* ($M = 31.03\%$, $SD = 8.38\%$), *Anarchic*

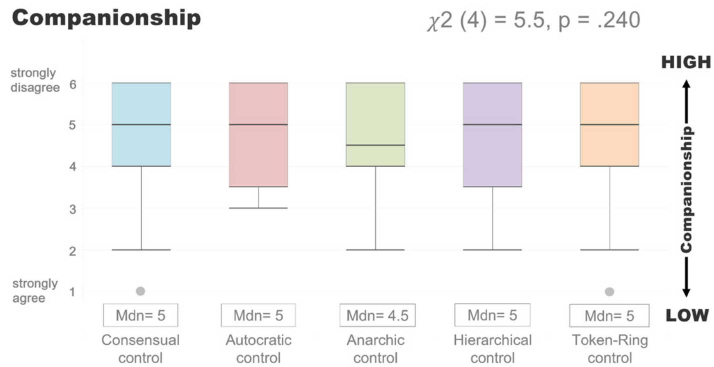


Figure 6. Companionship measurements (Lee & Robbins, 1995) across the different collaborative IVIS concepts with pairwise comparisons. The scale ranges from 1 = low companionship to 6 = high companionship. *Q: Even around people I know, I don't feel that I really belong.* Friedman test significant at $p < 0.05$.

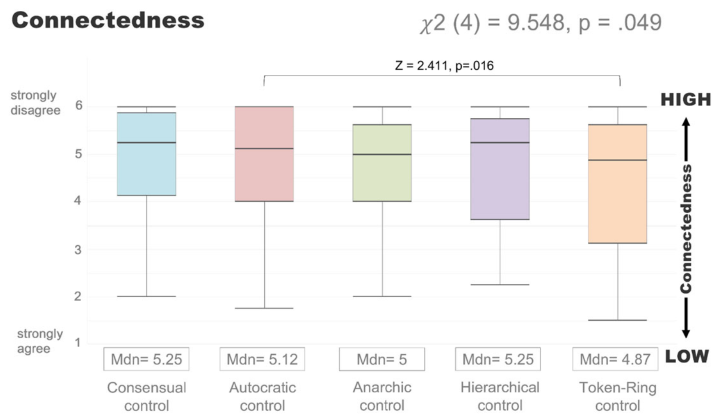


Figure 7. Connectedness measurements (Lee & Robbins, 1995) across the different collaborative IVIS concepts with pairwise comparisons. The scale ranges from 1 = low connectedness to 6 = high connectedness. *Q1: I feel so distant from the other people; Q2: I feel disconnected from the world around me; Q3: I don't feel related to anyone; Q4: I catch myself losing all sense of connectedness.* Friedman test significant at $p < 0.05$.

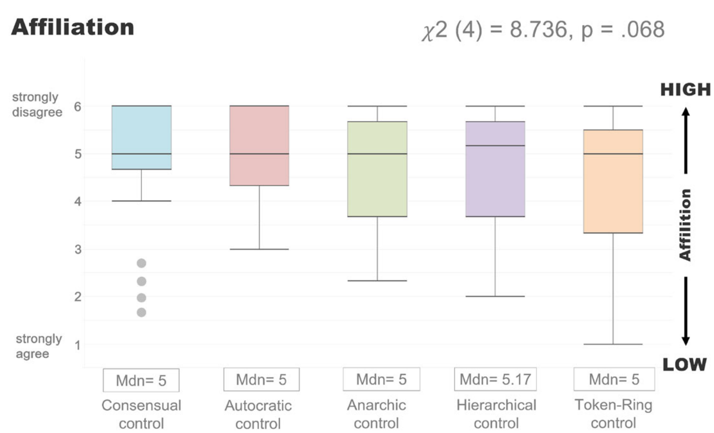


Figure 8. Affiliation measurements (Lee & Robbins, 1995) across the different collaborative IVIS concepts with pairwise comparisons. The scale ranges from 1 = low affiliation to 6 = high affiliation. *Q1: I don't feel I participate with anyone or any group; Q2: I have no sense of togetherness with my peers.; Q3: Even among my peers, there is no sense of brother/sisterhood.* Friedman test significant at $p < 0.05$.

control ($M = 29.88\%$, $SD = 7.36\%$), *Hierarchical control* ($M = 29.53\%$, $SD = 8.13\%$) and *Token-Ring control* ($M = 27.38\%$, $SD = 6.73\%$).

6.7. Subjective ranking

A Friedman test outlines that there is a statistically significant order of preference for the different IVIS concepts ($\chi_2(4) = 43.625, p < 0.001$). Post-hoc pairwise comparison shows a significant higher preferences for *Autocratic control* compared to *Hierarchical control* ($Z = -3.716, p = 0.002$), *Token-Ring control* ($Z = -4.585, p < .001$), and *Consensual control* ($Z = -5.850, p < 0.001$). Additionally, there is a significant higher preference for *Anarchic control* compared to *Token-Ring control* ($Z = -2.925, p = 0.034$) and *Consensual control* ($Z = -4.190, p < 0.001$). Figure 12 outlines the ranking per concept, ranging from 1 = most preferred to 5 = least preferred with a median score of 2 for *Autocratic and Anarchic control*, media score of 3 for *Hierarchical control*, 4 for *Token-Ring control*, and 5 for *Consensual control.*

6.8. Qualitative feedback

The results of the qualitative data analysis, conducted with the responses to the open-ended questions concerning each concept (both individually and the final interview), revealed both positive and negative aspects in relation to each concept. In the following, we report on the individual characteristics outlined by the participants in combination with the number of statements (Cnt#) and quotes (#P for passengers, #D for drivers).

The Consensual control concept enables both the driver and the passenger to have more control over choices and decisions (Cnt#6) and is described as a high level of collaboration (Cnt#11). However, insights outline that especially *Consensual control* is distracting the driver heavily due to the notifications (Cnt#20; e.g., "*It was highly distracting, because of checking and approving*" , D#4). Besides, drivers, as well as passengers, feel limited in their execution possibilities (Cnt#17; e.g., "*I could just do my thing*", D#11) because they can not control functions alone which is perceived as time-consuming, not efficient and a factor of stress increase (e.g., "*It takes so long to perform a task*", D#4). From a passenger point of view, *Consensual control* enables to be involved in decision making, feels more seen by the driver, and provides the possibility to propose changes (e.g., "*I can also share things and the system helps me to communicate with the driver*", P#12), especially in situations where negotiating is not able or appreciated (e.g., Uber or taxi rides, "*If we take a Uber, we can suggest things*", P#2).

The Token-Ring control concept gets described as a structured collaboration since only one person per time can control (Cnt#9). However, this at the same time induces power roles (Cnt#9) and is perceived as unfair (Cnt#3). Even though the switching token encourages communication (Cnt#2), participants remarked that experiencing limited access to functions influences collaboration in the car negatively because of exclusion and evoked frustration (Cnt#9, e.g., "*I feel frustrated once the function was gone*", P#2). Additionally, the *Token-Ring concept* is mentally demanding because of understanding who has control over what functions when and why (Cnt#4; e.g., "*I kept thinking about the functions and I had to check who had access*", D#1) which let drivers feel more distracted (Cnt#8; e.g, "*It was distractive because menus appeared and disappeared*", D#13).

The Hierarchical control concept enables to perform tasks in parallel (Cnt#6) while it also incorporates sharing a screen for certain functionalities (Cnt#5) which participants describe as fostering collaboration (Cnt#9). Having access to functions on a dedicated screen is additionally associated with lowering power dynamics and empowering the passenger (Cnt#13). Overall, using the driver screen sometimes feels more natural for the passenger and is faster in case the required menu is already open, even though the physical workload for reaching out to the display remains higher (e.g., "*If feels more efficient to use the screen with the already opened menu*", P#6, "*The physical workload was higher when using the drivers' screen*", P#16). Although passengers feel a lack of control due to limited access to functions on their screen (Cnt#7), drivers reported that providing passengers only access to dedicated menus prevents misuse and supports privacy concerning personal data (e.g., messages, calendar) (Cnt#3; e.g., "*I can decide what I would like to turn towards them. So they don't need to go through private messages*", D#1).

The Anarchic control concept is associated with an efficient way of collaboration (Cnt#9) and a better driver support (compared to the other concepts) (Cnt#6), because it enables to perform tasks in parallel due to two IVIS screens (Cnt#16; e.g., "*I have my own screen and we both can do things in parallel which is for me the most efficient way*", P#3). Since it does not limit access to menus (Cnt#9), especially the passengers feel more empowered (Cnt#13; e.g., "*I can decide any moment what I want to work on and where I want to assist*", P#8) and overall, participants describe this as fair (Cnt#8; e.g., "*It was nice that we both could do stuff*", D#1). Additionally, with the *Anarchic control* concept, drivers report being less distracted (Cnt#14), and also passengers have the feeling of not distracting the driver because there is no interference between them when using an IVIS screen (Cnt#18). However, drivers (3 out of 16) reported being mentally distracted due to thinking about what the passenger is currently doing on the dedicated screen (e.g., "*I do not really know what the other one is doing*", D#16). Besides, having two IVIS screens let some of the participants (3 out of 32) feel disconnected from the driver (e.g., "*I feel a bit separated from the driver because I just operate on my screen*", P#2) and from the driver perspective, having two screens requires more trust towards the passenger.

The Autocratic control concept is the concept the participants reported to be used to and thus they describe it as the most natural way of driver-passenger collaboration (Cnt#9). Overall, participants mentioned that *Autocratic control* supports collaboration (Cnt#11), enables communication (Cnt#4), and is fair (Cnt#2; "*It felt fair and I could do*

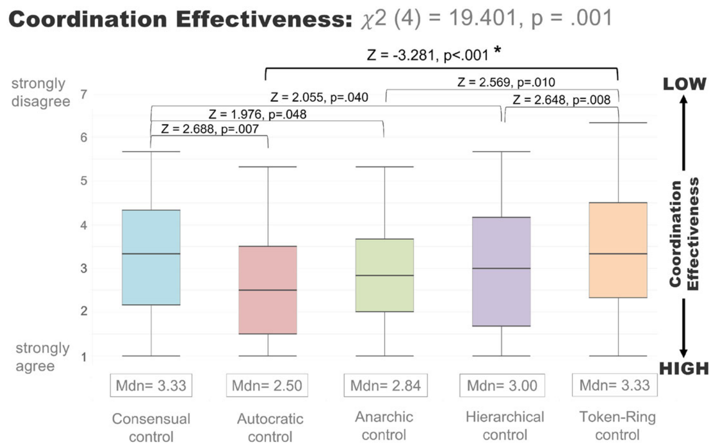


Figure 9. Coordination effectiveness measurements (Paul et al., 2016) across the different collaborative IVIS concepts with pairwise comparisons. The diagram presents the average coordination effectiveness, measured through the following three questions: *Q1: I am satisfied with my communication with the team members. Q2: There was a clear sense of direction during discussions with the team members. Q3: The interactions between the group members were well organized.* The scale ranges from 1 = high coordination effectiveness to 7 = low coordination effectiveness. Friedman test significant at $p < 0.05$. Bonferroni-corrected ($\alpha = 0.005$) Wilcoxon signed-rank post-hoc tests marked with *.

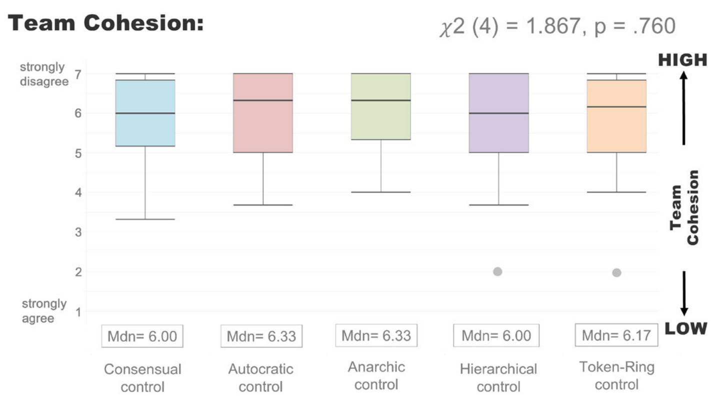


Figure 10. Team cohesion measurements (Paul et al., 2016) across the different collaborative IVIS concepts with pairwise comparisons. The diagram presents the average team cohesion, measured through the following three questions: *Q1: Dealing with the members of the team often left me feeling irritated and frustrated. Q2: I had unpleasant experiences with the team. Q3: Negative feelings between me and the team tended to pull us apart*. The scale ranges from 1 = low team cohesion to 7 = high team cohesion. Friedman test significant at $p < 0.05$.

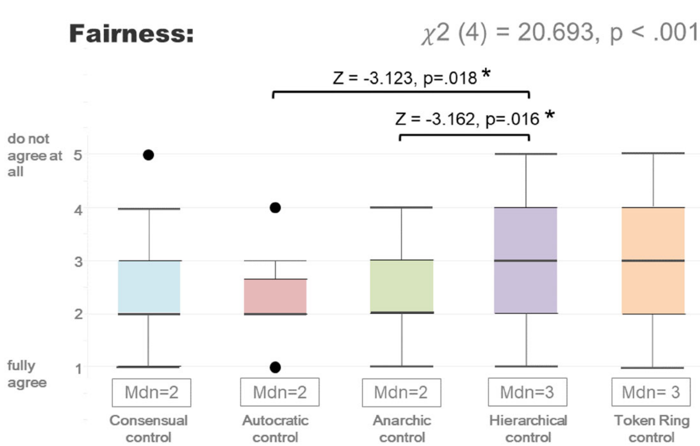


Figure 11. Distribution of the perceived fairness of each collaborative IVIS concept (1 = fully agree, 5 = do not agree at all) (*Q: I think the distribution of the operating options among the group members was fair*) Friedman test significant at $p < 0.05$. Bonferroni-corrected ($\alpha = 0.005$) Wilcoxon signed-rank post-hoc tests marked with *.

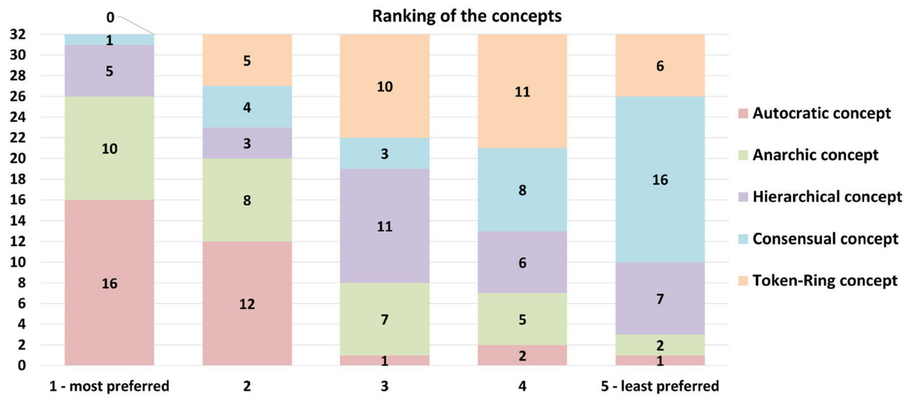


Figure 12. Visual overview of the subjective ranking of each collaborative IVIS concept. The far left bar demonstrates the voting of the most preferred choices, and the far right bar shows the least preferred options selected.

everything I wanted", P#14) due to sharing a single IVIS screen (Cnt#10; "*I like the one screen actually I think that is more collaborative*", D#16). However, a single screen is also associated with inducing power dynamics and hierarchies (Cnt#7; e.g.,"*I was more dependent on the driver*", P#4). Besides, drivers report that whenever the screen gets used by the passenger, they feel distracted (Cnt#11; e.g., "*I was constantly looking at the screen once the passenger did something*", D#12) and interventions are not possible (Cnt#4; "*It limits us doing our own thing*", P#1).

7. Discussion

In this article, we report how five different concepts, applied to IVISs, can exemplify different collaborative approaches and affect the perceived collaboration between a driver and a front-seat passenger. Our results show that the nature of the IVIS concept – how an IVIS is set up to facilitate collaboration – plays a significant role in drivers' and passengers' perceived team performance, social connectedness, and fairness. In this section, we link the findings to our hypotheses and discuss design recommendations for better driver-passenger collaboration in future cars.

7.1. Implications of collaborative IVIS on social connectedness, fairness, and team performance

As outlined by our results, social connectedness, fairness as well as team performance are independent of the driver/passenger role and gender-pair representation. Social connectedness, especially belongingness and connectedness get significantly influenced by the collaborative IVIS concept while this does not hold for companionship and affiliation which leads us to partially accept *H1 – the type of collaborative IVIS has an effect on social connectedness in terms of belongingness and connectedness*. With regard to the two metrics of team performance, while the IVIS concepts have an effect on coordination effectiveness, this does not apply to team cohesion. Thus, we partially accept *H2 – the type of collaborative IVIS has an effect on team performance in terms of coordination effectiveness*. Furthermore, our insights indicated that the concepts have an effect on perceived fairness, which leads us to accept *H3 – the type of collaborative IVIS has an effect on perceived fairness*.

Since each of the IVIS concepts evokes a good affiliation and companionship, we argue that in relation to previous work, all concepts allow for social interaction (Wong & Csíkszentmihályi, 1991), support the establishment of self-esteem (Lee & Robbins, 1995), well-being (Rook, 1987), and are perceived as socially satisfying (Rook, 1987). Even though each concept enables the driver and the passenger to connect with one another (connectedness), no concept supports a high feeling of belongingness. This can be potentially due to a limitation of our study set-up with reduced communication due to pre-defined tasks while it can also be induced by the in-car environment of sitting next to each other without maintained face-to-face communication (Fischer et al., 2014). In addition, *Token-Ring control* and *Anarchic control* scored lowest on belongingness which we relate due to qualitative insights to anticipated frustration and missing awareness of what the other user is currently doing on their screen (e.g., Tam & Greenberg, 2006). Nonetheless, collaboration gets promoted by all IVIS concepts, as represented by high levels of team cohesion, although collaboration is not as effective for every concept. Especially *Token-Ring control* impacts effectiveness negatively due to restricted menu access, compared to *Autocratic control* that provides a shared screen with full menu access. In addition, *Consensual control* is least effective due to a high time consumption for task execution, which is in line with previous work (Plaumann et al., 2016). An interesting point to note is that the *Autocratic control* (our baseline condition representing the status quo of IVIS setups) leads towards best coordination effectiveness, is users' preferred choice, and additionally scores high for social connectedness. However, eye-tracking data shows that this concept causes major driver distraction whenever the passenger interacts with the shared screen. We posit that the conventional single-screen setup is most natural and familiar to users (Zajonc, 2001) and thus fosters a sense of connectedness by default since the interaction takes place at a "common ground." However, since the passenger interacts on the driver's IVIS screen close to the driver's line of sight, this leads to the observed increased driver distraction. In contrast, our data show that *Hierarchical control* also leads to high coordination effectiveness and social connectedness, however, without any evidence of driving performance impact. Drivers also report a high perceived distraction when receiving pop-up notifications induced by *Consensual control*, which is in line with a high eyes-off-the-road time when passengers send requests. In general, any IVIS concept where the passenger interaction happens in the vicinity of the driver's display, or explicitly requires driver attention, causes driver distraction, which is in alignment with expectation. Even though the driver or passenger role itself has no effect on social connectedness, team performance, and fairness, our results indicate that the different IVIS concepts have an influence on the overall perception of fairness. *Autocratic and Anarchic control* are perceived as most fair and additionally, these two concepts are the most preferred ones. Based on qualitative insights, we argue, that fairness relates, on the one hand, to unlimited access to menus and on the other hand to the synchronous execution of functions without time restrictions. However, participant's choices can be biased by their previous experiences concerning IVIS set-ups (Zajonc, 2001), since having a single IVIS screen only (Autocratic control) or two identical IVIS screens are the most prominent ones available on the market.

Although participants tend to prefer the *Autocratic and Anarchic IVIS* over more novel collaborative IVIS approaches, both quantitative and qualitative data together highlight characteristics that support collaboration through social connectedness and team performance and mitigate driver distraction. We summarize this in the design recommendations below (for an overview see Figure 13).

7.2. Challenges and recommendations to support driver-passenger collaboration

7.2.1. One IVIS screen vs. two IVIS screens

While user preferences tend to favor a single IVIS screen because it lets them connect and belong better to one another, quantitative insights provide strong evidence that this highly distracts the driver when the passenger uses the screen. In addition, our insights are in line with previous research that highlights that people prefer familiar concepts with which they have already gained experience over novel concepts (Zajonc, 2001). If we want to facilitate collaboration and social interaction by ensuring driving safety, we, therefore, recommend two IVIS screens. According to our insights, providing the front-seat passenger with an individual screen mitigates subjective driver distraction and fosters efficient assistance since tasks can be performed in parallel. Besides that, it makes a car ride more convenient (Berger et al., 2021) and enhances passenger experience (Berger et al., 2019; Gridling et al., 2012). However, merely the presence of two IVIS screens does not guarantee optimal collaboration and a sense of connectedness, belongingness, or team spirit – as evidenced by our results (Figure 14).

> Providing the driver and the passenger with a dedicated IVIS screen mitigates subjective driver distraction while still enabling collaboration.

Figure 13. Challenges/recommendations to best support driver-passenger collaboration refer to the decision of providing a single IVIS screen or rather two IVIS screens, balancing power roles, creating situational awareness for the driver, encouraging active communication, and considering driver's privacy under the level of trust towards the passenger. (Bootstrap icons).

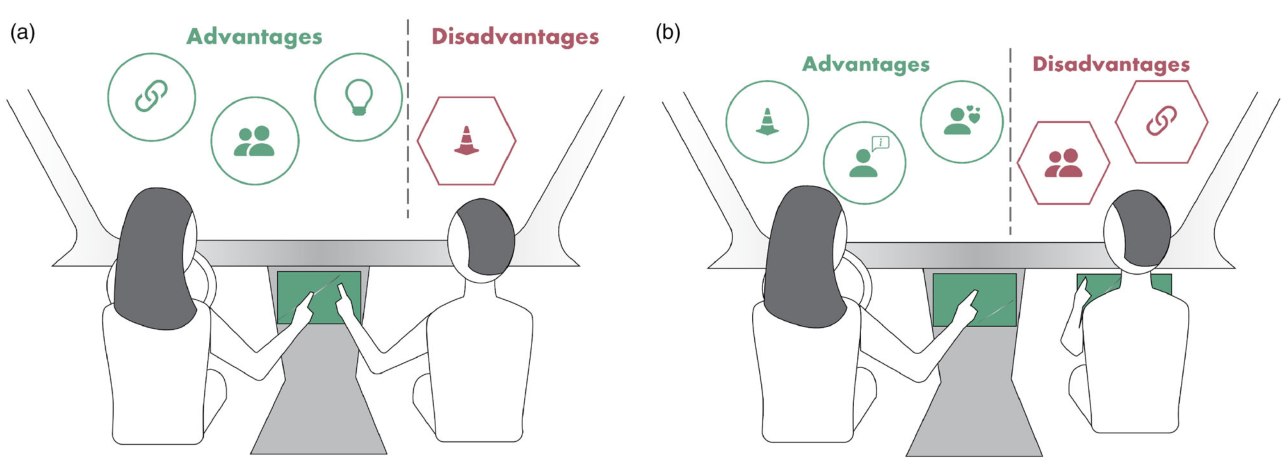


Figure 14. Illustration of the advantages and disadvantages of one IVIS screen (left illustration) vs. two IVIS screens (right illustration). (Bootstrap icons). (a) **Advantages:** fosters connectedness and belongingness, familiarity. **Disadvantage:** distracts the driver. (b) **Advantages:** ensures driving safety, efficient assistance, more convenience. **Disadvantage:** no guaranteed belongingness and connectedness.

7.2.2. Balancing power roles in the car

Having a single screen make passengers feel obligated to ask for allowance/permission to use the screen. This induces power dynamics and limits collaboration from the passengers' perspective. Since the driver is in most cases the owner of the car who needs to maintain safe driving, we recommend letting the driver decide which functions to delegate to the passengers. This enables passengers to assist with specific tasks, let them feel empowered while it maintains the driver as the main user. Additionally, it gives the driver the possibility to request assistance for those tasks where support is most urgently needed and prevents passengers to perform tasks subconsciously or without consent (Figure 15).

> Letting the owner of the car decide which functions to delegate to the passenger empowers passengers and enables them to request support for the most urgently needed tasks.

7.2.3. Create situational awareness

According to our results, drivers seek insights into changes the passenger is going to make. In addition, passengers tend to use the driver screen, whenever the required menu is already opened there because it costs less effort and saves time. However, it increases driver distraction. To overcome this, we recommend designing for a higher situational awareness, which in general can reduce conflicts and support collaboration (Dourish & Bellotti, 1992; Tam & Greenberg, 2006). A possible solution can be to manually enable the synchronization of the drivers' screen on the passenger screen. In addition, the driver requires feedback on changes made by the passenger, especially if there is no dedicated audio feedback available such as when changing the music or the radio channel. Possible solutions might range from notifications on a head-up display or instrument cluster, which should be investigated in future work (Figure 16).

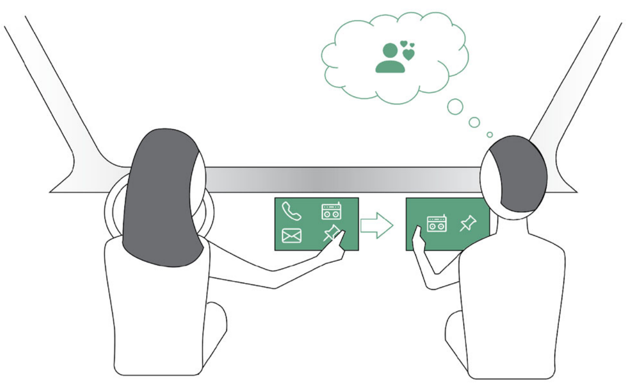


Figure 15. Illustration of empowering the passenger and minimizing power roles by delegating IVIS functions towards the passenger IVIS screen. (Bootstrap icons).

> Designing for a high level of situational awareness lowers driver distraction, reduces conflicts, and supports collaboration.

7.2.4. Active communication vs. technology-supported communication

An obvious and trivial way to enhance collaboration would be to communicate verbally and reach an agreement before either the driver or passenger interacts with the IVIS and makes an agreed-upon decision. However, in social, familiar driving settings, collaboration does not require active agreement of the driver, since it is time-consuming and distracts the driver. In addition, changes cannot be anticipated quickly or alone which might be required in dense traffic situations where the driver wants to explicitly seek passenger support. Thus, only active communication is preferred especially when the driver trusts the passenger (Meschtscherjakov et al., 2017). However, in situations where communication is either limited, cannot be ensured (e.g., taxi ride) (Inbar & Tractinsky, 2011) or trust towards the passenger is limited (e.g., kids on board) (Berger et al., 2021; Inbar & Tractinsky, 2011), technology can be used as a mediator to foster collaboration as we explored in this study. Subsequently, we recommend providing the possibility to send out recommendations and to accept/decline accordingly to enable passengers to request changes and let them be involved more (Figure 17).

> Use technology as a mediator to foster collaboration, especially in situations where active communication is limited or cannot be ensured.

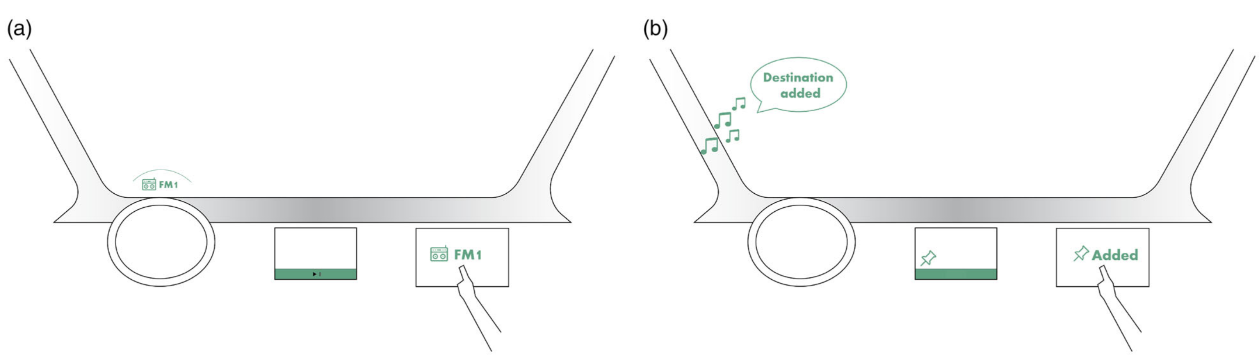


Figure 16. Illustration of possibilities to enhance situational awareness for the driver concerning changes or interactions the passenger makes. (Bootstrap icons). (a) Informing the driver about passengers' changes/interaction on the head-up display. (b) Informing the driver about passengers' changes/interactions via audio notifications.

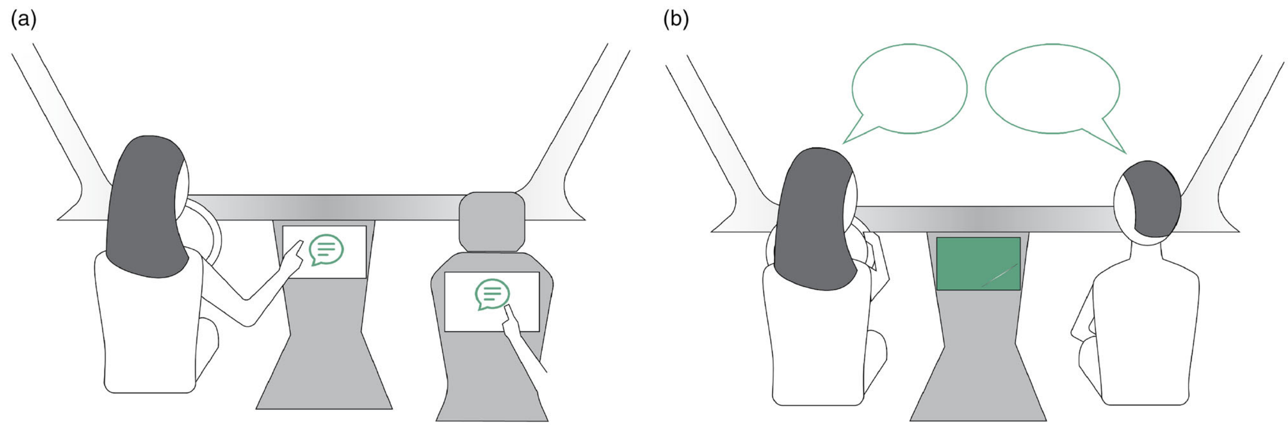


Figure 17. Illustration of different modes of communication in a car. (Bootstrap icons). (a) Enabling technology-supported communication between the driver and a rear-seat passenger e.g., in a taxi. (b) Active communication between the driver and the passenger when trust is guaranteed. (Bootstrap icons).

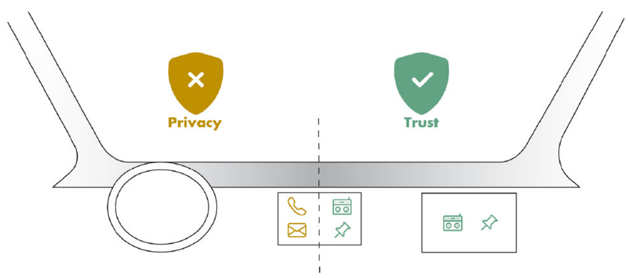


Figure 18. Illustration of privacy and trust aspects when it comes to collaboration in the car using IVIS functions. This example shows that for instance access to messages or phone contacts is only allowed by the driver. While for instance the radio or the navigation menu can be shared with the passenger. (Bootstrap icons).

7.2.5. Social adaptation to support fairness, privacy, and trust

Taken together, there is the need to balance fairness and privacy depending on the trust towards passengers to support optimal collaboration. While two screens with unlimited access to functions support fairness best and, in addition, mitigate perceived driver distraction (see Section 7.2.1), this set-up requires high trust towards the passenger which might not be given in all riding scenarios (Meschtscherjakov et al., 2017). Additionally, drivers do not want to unveil all types of data, especially private ones such as messages or contact details. Even though full menu access results in an efficient collaboration, it interferes with drivers' privacy needs and trust levels (see Section 7.2.2). A possible solution might be to allow for different modes of collaboration depending on the social situation in the car (e.g., the relationship between occupants, physical and mental ability to assist (Berger et al., 2021; Inbar & Tractinsky, 2011). Future research, therefore, is needed to investigate the effect of social riding scenarios on driver-passenger collaboration (Figure 18).

> Consider possible privacy concerns and the level of trust between the driver and the passenger to establish fairness for more efficient collaboration.

7.3. Limitations

Even though we did not observe any risky behavior or artificial situations due to the interaction in the car, a driving simulator study has a limitation when it comes to ecological validity. Especially the room situation might entice participants to not take the experimental set-up as seriously enough or to drive more riskily than in (more) realistic driving scenarios. Future work should therefore investigate how these concepts perform in a real-world scenario, especially concerning driver distraction. In terms of external validity, the driving area and the perceived safety risks (street condition, environment) can thus have an impact on the applicability of our findings across cultural contexts. Additionally, our study was conducted in Mid-Europe with a specific demographic of age and culture under a limited exploration of contextual dimensions. Different contextual characteristics, e.g. various socio-cultural backgrounds of users might relate to varying expectations of in-car collaboration and thus have a different impact on social collaboration. As future work, we, therefore, outline a more thorough exploration of the contextual dimensions of in-car collaboration.

7.4. Future work: a systematical exploration of in-car collaboration based on contextual factors

7.4.1. Exploring in-car collaborative systems with the guidelines in mind

Our simulator study provides valuable insights into how an IVIS can be designed for the dedicated collaborative support among a driver and a front-seat passenger to enhance perceived team performance, social connectedness, and fairness. To explore the future of in-car collaboration in more detail we see the need to explore how our recommendations can be applied to in-car systems and how they support collaboration. Therefore, as a next step, we are working on a follow-up study that focuses on the design of situational awareness. We particularly explore possibilities on how to inform the driver about changes made by the front-seat passenger and investigate the impact on collaboration, trust, and driver distraction. Besides, we want to understand how the perceived collaboration changes when the driver seeks support from a back-seat passenger compared to our insights related to driver-front-seat passenger collaboration.

Besides, more extensive studies are needed to understand how the five concepts perform in different contextual settings with a focus on exploring opportunities to empower passengers and encourage drivers to lower their barriers to seeking assistance.

7.4.2. Social context

To fully explore the social context of in-car collaboration of manually driven cars, future work is needed to (a) explore how the five concepts can be applied to enable collaboration among the driver and several passengers (e.g., front-seat and back-seat passengers together) and (b) how perceived collaboration changes according to occupants relationships (e.g., family relationship vs. work relationship, strangers). Particularly to understand how to design for collaboration among strangers (e.g., ride-sharing scenario) where passengers hesitate with providing assistance (Gridling et al., 2012). Additionally, we see the potential to investigate how the concepts can be used or modified to seek support from children too.

7.4.3. Personal context

Our first insights concerning different collaborative IVIS concepts show no difference among same-gender and mixed-gender pairs and also no difference among diverse relationships (work vs friendship). To fully explore the *personal context*, we see the importance to investigate how these concepts can be applied to enable also less technically-knowledgeable people to support the driver. Additionally, future work is required to understand how these concepts can be of use to design collaborative in-car systems in a way to be also used by passengers that require special needs.

7.4.4. Context of the context

To ensure scalability of our results we see the necessity to investigate how collaboration in general, and how particularly these five concepts perform among occupants having different or diverse cultural backgrounds. For instance, Li et al. report on differences, between Germany and China in terms of driving culture (e.g., lane changing frequency, right of way, merging habits), and outline the opportunity to design emotion-aware in-car interfaces (Li et al., 2019). This highlights the importance of the socio-cultural context in which these interactions take place, and it is possible that the collaborative aspects are dependent on the context of the interaction. Additionally, the environment itself, such as the driving area (e.g., highway, rural area, city) in different countries is a possible influencing factor on social collaboration which provides areas for future work.

7.4.5. Technological context

While we explored how the five concepts can be applied to the IVIS, future research should explore whether and how these concepts can be used to support collaboration by means of external devices (e.g., smartphones, tablets), in combination with an IVIS.

7.4.6. Spatial context

While our research particularly focused on the collaboration of occupants within a car, we see the potential to extend the scope of applications toward vehicle-vehicle collaboration or vehicle-external user collaboration, with the goal to enhance social interaction and general in-car experience. An example can be to explore how the concepts can provide users from outside (e.g., friends or family members at home) with the possibility to support the driver with performing non-driving-related activities. Additionally, we see the potential to collaborate among different cars, particularly in the case of a group traveling together to the same destination but distributed among different vehicles.

7.4.7. Temporal context

The *temporal context* can have an influence on general collaboration, particularly on the in-car experience. Thus, future work is needed to understand how long-term usage of the concepts impacts social collaboration and experience. Additionally, the task itself, particularly the task duration can influence how collaboration is perceived. Thus, we see the need to investigate the impact of task complexity on drivers' and passengers' perceived social experience.

Besides, to establish certain aspects of the concepts and to apply our recommendations in the next generation of manually driven cars, future studies should be conducted in a (more) realistic driving/simulator setting. This will allow for measuring the impact on safety (e.g., assessing driving performance and drivers' distraction) more accurately.

8. Conclusion

In this article, we explored the role that social connectedness, fairness, and team performance have on driver-passenger collaboration in manually driven cars. We, therefore, designed five different collaborative IVIS concepts based on the distribution of control authority over IVIS functionalities. Through the results of a simulator study, we found that the type of collaborative IVIS concept influences the perceived social connectedness in terms of group belongingness and connectedness as well as fairness and team performance in terms of coordination effectiveness. Especially *Autocratic control* leads towards a high social connectedness and team performance. However, the majority of drivers feel distracted once a passenger interacts with the screen. Providing two IVIS screens under *Anarchic* or *Hierarchical control* instead, empowers front-seat passengers, reduces power dynamics, and minimizes driver distraction caused by interacting passengers. Especially *Anarchic control* is perceived as fair by passengers. However, drivers have concerns about privacy, especially inside their own cars. With this work, we contribute by highlighting design aspects to support driver-passenger collaboration in future cars by designing for a higher level of social connectedness, fairness, and team performance. Additionally, we outline future research directions to explore in-car collaboration in more breadth and depth.

Notes

1. Unity 3D: https://unity.com/, last accessed June 28, 2022.
2. MQTT: https://mqtt.org/, last accessed June 28, 2022.

Ethical approval

The experiment has been approved by the Ethical Review Board (ERB) at Eindhoven University of Technology, reference number ERB2020ID177.

Disclosure statement

The authors hereby certify that, to the best of their knowledge, there are no conflicts of interest to disclose.

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Appendix A. Questionnaire items

Table A1. Overview of the questions from the Social Connectedness Scale (Lee & Robbins, 1995), asked to assess social connectedness in terms of companionship, connectedness, and affiliation.

Item	Question	1 (Strongly agree)	2	3	4	5	6 (Strongly disagree)
Companionship	Even around people I know, I don't feel that I really belong						
Connectedness	I feel so distant from the other people						
	I feel disconnected from the world around me.						
	I don't feel related to anyone.						
	I catch myself losing all sense of connectedness with society.						
Affiliation	I don't feel I participate with anyone or any group						
	I have no sense of togetherness with my peers.						
	Even among my friends, there is no sense of brother/sisterhood.						

Table A2. Community in self scale (Mashek et al, 2007), used to assess social connectedness in terms of belongingness.

How do you feel about the relationship between you and the other participant (driver/passenger) after using the system you just tested? Please select the image below that best describes your perception of belonging. The first image - the two separate circles (a) - demonstrates no belongingness between you and other participant. The last image - two nearly fully overlapping circles (g) - symbolizes a maximum positive belongingness between you and the other participant (maximum group membership).

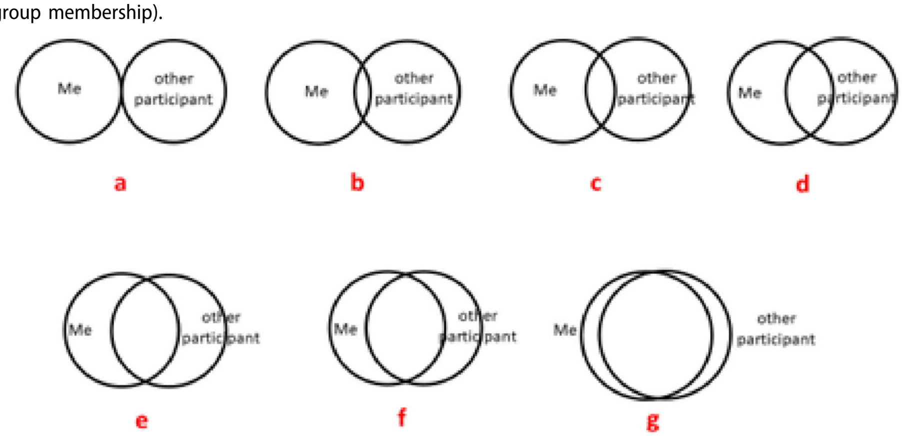

Table A3. Overview of the questions from the team performance questionnaire (Paul et al., 2016), asked to assess team performance in terms of coordination effectiveness and team cohesion.

Item	Question	1 (Strongly agree)	2	3	4	5	6	7 (Strongly disagree)
Coordination effectiveness	I am satisfied with my communication with the team members							
	There was a clear sense of direction during discussions with the team members							
	The interactions between the group members were well organized							
Team cohesion	Dealing with the members of the team often left me feeling irritated and frustrated							
	I had unpleasant experiences with the team							
	Negative feelings between me and the team tended to pull us apart							

Table A4. Self-defined questions asked to assess the perceived fairness of each concept.

Related to	Question	1 (Fully agree)	2 (Rather agree)	3 (Neither nor)	4 (Rather not agree)	5 (Do not agree at all)
Perception of different control possibilities	I think the distribution of the operating options among the group members was fair					
Perception of fairness support	I had the feeling that others had more operating options than I had					