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Nachhaltige Mobilität mit begrenzten Ressourcen: Erleben und Verhalten im Umgang mit der Reichweite von Elektrofahrzeugen

[Sustainable mobility with limited resources: Experience and behavior in dealing with electric vehicle range]

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Zusammenfassung

Ressourcenknappheit und nachhaltige Nutzung von Ressourcen sind zentrale Themen unserer Zeit. Das Thema nachhaltige Mobilität hat auch in der Verkehrspsychologie über die letzten Jahre zunehmend an Bedeutung gewonnen. Hierbei wird der Elektromobilität ein entscheidender Beitrag zur nachhaltigen Nutzung unserer Energieressourcen zugesprochen. Die Steigerung der Unabhängigkeit von Energieimporten, die mindestens lokale Emissionsfreiheit und die Möglichkeit erneuerbare Energien besser ins Stromnetz zu integrieren sind zentrale Vorteile der Elektromobilität. Eine potentielle Herausforderung für die Nutzer stellt jedoch die Interaktion mit den begrenzten Reichweitenressourcen dar.

Die vorliegende Dissertation beschäftigt sich mit dem Nutzererleben und -verhalten im Umgang mit der Reichweite von Elektrofahrzeugen. Zu Beginn des Forschungsprojekts „MINI E Berlin powered by Vattenfall", welches die Grundlage dieser Dissertation darstellt, gab es kaum veröffentlichte Studien zur Nutzerperspektive auf Reichweite. Das Ziel dieser Dissertation ist daher, ein detailliertes und theoriegeleitetes psychologisches Verständnis zentraler Facetten dieses Themenfelds zu erlangen.

Basierend auf übertragbaren Theorien und Konzepten aus verwandten Teilgebieten der angewandten Psychologie, wird in der Dissertation ein Modell entwickelt und getestet: Das Modell der adaptiven Kontrolle von Reichweitenressourcen. Ein Kernpunkt dieses Modells ist das Konzept der komfortablen Reichweite, welches eine psychologische Fundierung des vieldiskutierten Konzepts der Reichweitenangst darstellt. Denn im Alltag erleben Nutzer mit Elektrofahrzeugerfahrung bei einer für Mobilität in Deutschland relativ typischen Fahrleistung kaum Situationen, in denen es zu Reichweitenangst kommt. Die Reichweiteninteraktion ist eher von der Vermeidung und nicht vom Erleben von Reichweitenangst (Reichweitenstress) gekennzeichnet. Über die Analogie zum psychologischen Stress werden verschiedene Einflussvariablen auf die komfortable Reichweite identifiziert. Die komfortable Reichweite (der individuell präferierte Reichweitensicherheitspuffer) stellt sich als eine Variable dar, bei der es eine große interindividuelle Varianz gibt, die teilweise auf einer unterschiedlichen Stressresistenz zu beruhen scheint.

Insgesamt wird die, sich in vorangegangenen Studien abzeichnende, suboptimale Reichweitenausnutzung damit erklärt, dass es neben der technischen Reichweite drei psychologische Reichweitenschwellen gibt, die den Übergang von der objektiven physikalischen zur subjektiven psychologischen Reichweitensituation charakterisieren: (1) Die kompetente (für den Nutzer maximal erreichbare), (2) die performante (im Alltag verfügbare), und (3) die komfortable (die wirklich nutzbare) Reichweite. Es zeigt sich, dass 20-25% der im Alltag verfügbaren Reichweitenressourcen als psychologischer Sicherheitspuffer verlorengehen. Mit dem erworbenen Verständnis für die

Reichweiteninteraktion sollte es möglich werden besser fundierte Maßnahmen abzuleiten, um mit einer bestimmten Batteriekapazität mehr nutzbare Reichweitenressourcen zu erzielen und Nutzer bei einer nachhaltigeren Nutzung der Reichweitenressourcen zu unterstützen.

Einen weiteren Schwerpunkt der Dissertation bilden Interaktionsstile im Umgang mit den Reichweitenressourcen. In Analogie zu psychologischen Konzepten wie Fahrstilen und Bewältigungsstilen und basierend auf ersten Studien zu Ladestilen bei der Nutzung von Smartphones wird das Konzept des UBIS (user-battery interaction style) vorgeschlagen, als eine Tendenz sich mehr oder weniger aktiv mit den Batterieressourcen auseinanderzusetzen (z.B. bei Ladeentscheidungen). Es zeigt sich in der Tat, dass diese Variable, gemeinsam mit der komfortablen Reichweite, bestimmte Parameter des Ladeverhaltens aufklären kann und dabei auch eine gewisse Stabilität über die Zeit und über verschiedene Mensch-Technik-Systeme hinweg aufweist. Auch findet sich ein Zusammenhang zwischen dem UBIS und der nachhaltigen Interaktion mit den Energieressourcen in einem Elektromobilitätssystem.

Schließlich behandelt die Dissertation auch die Präferenzen für bestimmte Reichweitenauslegungen. Hier wird dem Befundmuster nachgegangen, dass die Reichweitenpräferenzen von Autokäufern scheinbar oftmals weit über den tatsächlichen Reichweitenbedürfnissen liegen. In der vorliegenden Arbeit wird diese Diskrepanz erstmals auf Basis von Daten potentieller Elektrofahrzeugkäufer mit praktischer Elektrofahrzeugerfahrung quantifiziert. Es zeigt sich, (1) dass solche Nutzer nicht unbedingt übertriebene Reichweitenerwartungen haben, (2) dass erlebte Reichweitenangst während der Nutzung und eine größere vertraute Reichweite bei Verbrennerfahrzeugen mit höheren Reichweitenpräferenzen einhergehen, (3) dass sich die Reichweitenpräferenzen mit zunehmender Erfahrung verringern, und (4) dass es mit zunehmender Erfahrung einen wachsenden Zusammenhang zwischen den tatsächlichen Mobilitätsbedürfnissen und den Reichweitenpräferenzen gibt. Dies weist auf die Wichtigkeit von praktischer Erfahrung für den breiten Erfolg von nachhaltigen Elektromobilitätssystemen hin.

Möglicherweise sind einige theoretische und methodische Entwicklungen aus dieser Arbeit auch auf ähnliche Mensch-Technik-Systeme und verwandte Fragestellungen der nachhaltigen Mobilität übertragbar. Implikationen für die Anwendung sind beispielsweise, dass eine verlässlich nutzbare Reichweite wichtiger ist als die Steigerung der maximalen Reichweite und dass Informations- und Assistenzsysteme für den Umgang mit der Reichweite darauf ausgelegt werden sollten, dass sie zu einer intensiven Auseinandersetzung mit der Reichweitendynamik anregen und damit den Kompetenzerwerb fördern sowie die Nutzer bei der alltäglichen Regulation der Reichweitenressourcen unterstützen, zum Beispiel indem sie die subjektive Kontrollierbarkeit der Reichweite erhöhen.

Summary

Scarcity of resources and sustainable use of resources are central issues of our time. In traffic psychology, the theme of sustainable mobility has also taken on increased importance in recent years. Herein electric mobility has been ascribed a decisive role in the sustainable utilization of our energy resources. Less dependence on energy imports, zero-emissions (at least locally), and the potential for better integration of renewable energy sources into the power grid are central advantages of electric mobility. Yet, a potential challenge for users is the interaction with limited range resources.

The present dissertation focuses on user experience and behavior in dealing with electric vehicle range. Prior to the research project, “MINI E Berlin powered by Vattenfall”, which constitutes the basis for this dissertation, there were rarely any published studies concerning the user perspective on range. Consequently, the goal of this dissertation is to obtain a detailed and theory-driven psychological understanding of the central facets of this topic.

Based on transferrable theories and concepts from related areas of applied psychology, a model is developed and tested within this dissertation: the adaptive control of range resources (ACOR) model. A key point of this model is the concept of comfortable range, which represents a psychological foundation of the widely discussed concept of range anxiety. This is because, in everyday life, users with practical electric vehicle experience rarely experience situations in which range anxiety occurs, given a relatively typical mileage for mobility in Germany. Rather, range interaction is characterized by the avoidance, not the experience, of range anxiety (i.e., range stress). Via the analogy to psychological stress, different variables that influence comfortable range are identified. The comfortable range (i.e., an individual’s preferred range safety buffer) appears to be a variable that shows a high interindividual variance, which partly seems to be predicated upon differing stress resistance.

In sum, the suboptimal range utilization found in previous studies is explained by the proposition that there are three psychological range levels besides the technical range that characterize the transition from the objective physical to the subjective psychological range situation: (1) The competent (i.e., maximum achievable for the user), (2) the performant (i.e., available on an everyday basis) and (3) the comfortable (i.e., actual usable) range. It shows that 20-25% of the range resources that are available on an everyday basis are lost as a psychological safety buffer. With the acquired understanding of user-range interaction, it should become possible to develop better informed strategies for attaining higher actual battery usage relative to battery capacity, as well as supporting users in the sustainable use of range resources.

Another focus of the dissertation is interaction styles in dealing with range resources. Analogous to the psychological concepts of driving styles and coping styles and based on earlier studies of mobile phone use charging styles, the concept of UBIS (user-battery interaction style) is proposed, as a tendency to deal with the battery resources rather more or less actively (e.g., in charging decisions). Indeed, it shows that this variable, together with comfortable range, can explain certain parameters of charging behavior, and also shows temporal stability as well as stability across different human-machine-systems. Moreover, a relationship between UBIS and a sustainable interaction with energy resources in an electric mobility system is found.

Finally, the dissertation also covers the preferences for certain range configurations. Here, the pattern of previous research findings indicate that range preferences of car buyers are often far greater than their actual range needs. In the present work, this discrepancy is quantified for the first time based on data from potential electric car customers with practical electric vehicle experience. It shows that, (1) such users do not necessarily have exaggerated range preferences, (2) experienced range anxiety during usage and a higher familiar range of combustion cars are associated with higher range preferences, (3) range preferences decrease with increasing experience, and (4) the correlation between actual range needs and range preferences grows as practical experience increases. This highlights the importance of practical experience for the broad success of sustainable electric mobility systems.

Potentially, some theoretical and methodological developments from this work are also transferrable to similar human-machine-systems as well as related issues in the field of sustainable mobility. Implications for application are, for example, that a reliable usable range is more important than an increase in maximum possible range. Moreover, the design of information and assistance systems for facilitation of the user-range interaction must be targeted at encouraging more intensive interaction with range dynamics, promoting skill acquisition as well as supporting users in their daily regulation of range resources, for example by enhancing subjective controllability of range.

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I Synopse

1 Einleitung

Wie weit komme ich damit? Dies ist häufig eine der ersten Fragen von Elektrofahrzeuginteressenten. Die Reichweite eines Elektrofahrzeugs[1] ist, zumindest subjektiv, eine knappe Ressource. Die Knappheit natürlicher und damit teilweise auch energetischer Ressourcen ist ein Kernthema unserer Zeit (Simpson, Toman, & Ayres, 2004). Ein differenziertes Verständnis des Umgangs mit solchen knappen Ressourcen ist damit auch eine Forschungsaufgabe der angewandten Psychologie. Wie erleben Menschen knappe Ressourcen? Wie können Systeme so gestalten werden, dass der effiziente Umgang mit knappen Ressourcen als möglichst angenehm (wenig beanspruchend) empfunden wird? Dies sind essentielle Forschungsfragen der Psychologie knapper Ressourcen. Das Elektrofahrzeug ist dabei ein Beispiel für ein Mensch-Technik-System, in dem Nutzer gegenwärtig mit knappen energetischen Ressourcen, in Form der begrenzten Reichweite, interagieren.

Bis zum Beginn dieser Dissertation existierten kaum Veröffentlichungen über das alltägliche Erleben und Verhalten von Elektrofahrzeugnutzern im Umgang mit der Reichweite. Das Ziel war daher, ein durch psychologische Theorien und methodische Neuentwicklungen fundiertes Bild der Nutzerperspektive auf Reichweite zu erarbeiten und damit auch einen Beitrag zur Fortentwicklung der Psychologie knapper Ressourcen, insbesondere zur Verkehrspsychologie im Bereich der nachhaltigen Mobilität, zu leisten. Dies wurde möglich durch die Beteiligung an der Feldstudie „MINI E Berlin powered by Vattenfall" (Krems, Weinmann, Weber, Westermann, & Albayrak, 2013), welche in den Jahren 2009 bis 2010 ein Elektromobilitätssystem[2] im urbanen Umfeld testete.

Mit Abschluss dieser Dissertation liegen vier in Erstautorenschaft veröffentlichte Artikel in Fachzeitschriften zum Thema „Nutzer und Reichweite" vor. Diese bilden die Grundlage für die vorliegende Dissertation. Darüber hinaus liegen drei Buchkapitel vor (Franke, Bühler, Cocron, Neumann, & Krems, 2012; Franke, Cocron, Bühler, Neumann, & Krems, 2012; Pichelmann, Franke, & Krems, 2013), welche inhaltlich im Zusammenhang mit dieser Dissertation stehen und auf die daher an entsprechenden Stellen referenziert wird.

Die folgende Synopse konzentriert sich insbesondere auf die Darstellung des Forschungsrahmens (siehe Abschnitt 2) sowie auf eine zusammenfassende Darstellung des über die Artikel 1-3

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[1] Mit Elektrofahrzeug ist in dieser Arbeit stets ein rein batterieelektrischer (vollelektrischer) PKW gemeint. An vielen Stellen sind die Aussagen aber auch auf Plug-in-Hybride und batterieelektrische Fahrzeuge mit Range Extender übertragbar.

[2] Mit dem Begriff Elektromobilitätssystem wird in dieser Arbeit eine bestimmte Konfiguration von Elektrofahrzeug, Ladeinfrastruktur und gegebenenfalls verfügbaren Zusatzdiensten (z.B. Mobilitätspakete) bezeichnet.

entwickelten Modells (siehe Abschnitt 4) und des Bezugs zu bestehenden Modellen (siehe Abschnitt 3). Die methodischen Aspekte sowie die konkreten Hypothesentests und explorativen Analysen sind in den einzelnen Artikeln im Detail ausgeführt. Daher wird in Abschnitt 5 (Methodik) und Abschnitt 6.1 (Befunde) jeweils nur ein knapper Überblick gegeben und auf zentrale Abschnitte in den Artikeln verwiesen. Abschließend werden die Befunde aus der Perspektive ihrer theoretischen und praktischen Implikationen diskutiert (Abschnitt 6.2 und 6.3), die Studienmethodik kritisch reflektiert (6.4) und der mögliche Beitrag der Dissertation zur psychologischen Forschung expliziert (6.5). Nach dieser Synopse folgen die vier Artikel. Diese sind:

Artikel 1 – Franke, T., Neumann, I., Bühler, F., Cocron, P., & Krems, J. F. (2012). Experiencing range in an electric vehicle: Understanding psychological barriers. *Applied Psychology*, *61*(3), 368-391. http://dx.doi.org/10.1111/j.1464-0597.2011.00474.x

Artikel 2 – Franke, T., & Krems, J. F. (2013). Interacting with limited mobility resources: Psychological range levels in electric vehicle use. *Transportation Research Part A: Policy and Practice*, *48*, 109-122. http://dx.doi.org/10.1016/j.tra.2012.10.010 (Teil des Special Issue "Psychology of Sustainable Travel Behavior")

Artikel 3 – Franke, T., & Krems, J. F. (2013). Understanding charging behaviour of electric vehicle users. *Transportation Research Part F: Traffic Psychology and Behaviour*, *21*, 75-89. http://dx.doi.org/10.1016/j.trf.2013.09.002

Artikel 4 – Franke, T., & Krems, J. F. (2013). What drives range preferences in electric vehicle users? *Transport Policy*, *30*, 56-62. http://dx.doi.org/10.1016/j.tranpol.2013.07.005

2 Forschungsrahmen & Forschungsziele

2.1 Einbettung der Dissertation in die angewandte Psychologie

Die vorliegende Dissertation beschäftigt sich mit einem auf den ersten Blick sehr spezifischen, aus der Anwendung motivierten Thema. Damit stellt sich gegebenenfalls die Frage, in welches Teilgebiet der angewandten Psychologie diese Arbeit einzuordnen ist und welchen Beitrag sie zur Fortentwicklung dieses Teilgebiets zu leisten versucht. Das Ziel dieser Dissertation ist, einen Beitrag zur Verkehrspsychologie zu leisten, wobei es möglich ist, dass die beforschten psychologischen Konzepte und Befunde teilweise auch auf Mensch-Technik-Systeme außerhalb des Verkehrsbereichs übertragbar sind (siehe zum Beispiel die Analogien in Artikel 3).

Während sich über lange Zeit ein überwiegender Teil der Verkehrspsychologie mit Aspekten der Fahrsicherheit beschäftigt hat, ist das Thema nachhaltige Mobilität in den letzten Jahren zunehmend in den Fokus gerückt[3]. Auch in anderen Gebieten der Mensch-Technik-Interaktion zeigt sich dieser Trend (Haslam & Waterson, 2013; Pierce, Strengers, Sengers, & Bødker, 2013). So ist 2013 schließlich sowohl ein Special Issue zum Thema „Ergonomics and Sustainability“ (Haslam & Waterson, 2013), als auch ein Special Issue zum Thema „Psychology of Sustainable Travel Behavior“ erschienen (Gehlert, Dziekan, & Gärling, 2013; Artikel 2 ist Teil dieser Ausgabe).

Eine zentrale Forschungsfrage dieses Teilgebiets besteht darin, wie man Menschen zu einem nachhaltigeren Mobilitätsverhalten motivieren kann (Gehlert et al., 2013). Die meisten Arbeiten fußen hierbei auf der Theorie des geplanten Verhaltens (Ajzen, 1991; Higham, Cohen, Peeters, & Gössling, 2013) und verwandten Modellen (Gatersleben, 2012). Der Fokus liegt hiermit meist darauf, wie man Personen zum Wechsel auf nachhaltigere Mobilitätsoptionen bewegen kann. Die psychologischen Prozesse während der Nutzung eines nachhaltigen Mobilitätssystems und die damit verknüpften Nachhaltigkeitspotentiale werden bisher weniger untersucht. Damit stellt eine stärkere Perspektive der Mensch-Technik-Interaktion unter Umständen eine Bereicherung für die Verkehrspsychologie der nachhaltigen Mobilität dar. Der Fokus dieser Perspektive sollte darauf liegen, wie man durch die nutzerfreundliche Gestaltung des technischen Systems ein besseres Nutzererleben und ein nachhaltigeres Nutzerverhalten erreichen kann (McIlroy, Stanton, & Harvey, 2013). Dabei sollte die Forschung, dem Ideal der Ingenieurspsychologie folgend, nicht nur ein bestimmtes technisches System bewerten, sondern die Leistungsfähigkeit und -grenzen von Nutzern

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[3] Zum Beispiel taucht in „Transportation Research Part F: Traffic Psychology and Behaviour“ der Begriff „sustainable mobility“ erstmalig 2003 auf. Auch in einer Scopus-Suche zu <"sustainable mobility" AND psychology> zeigt sich dieser Trend (vor 2003 stets <3 Publikationen pro Jahr, dann Anstieg, ab 2008 >10).

charakterisieren (Poulton, 1966) und dadurch die Ableitung eines nachhaltigen Designs möglich machen.

Die vorliegende Arbeit untersucht die Mensch-Technik-Interaktion auf Basis einer bestimmten Form der nachhaltigen Mobilität, der Elektromobilität. Dabei liegt der Fokus auf der Charakterisierung des Nutzererlebens und -verhaltens im Umgang mit der Reichweite. Denn wie im folgenden Abschnitt ausgeführt, kann die Elektromobilität ihr Nachhaltigkeitspotential erst dann voll ausschöpfen, wenn die Besonderheiten des Nutzererlebens und -verhaltens berücksichtigt werden. Die Dissertation versucht damit, die Verkehrspsychologie im Bereich der nachhaltigen Mobilität durch theoretische (siehe Abschnitt 4) und methodische (siehe Abschnitt 5) Neuentwicklungen zu bereichern.

2.2 Nutzer und Reichweite von Elektromobilitätssystemen

Elektrofahrzeuge sind eine vielversprechende Form nachhaltiger Mobilität. Die Reichweite stellt jedoch gegenwärtig und potentiell auch langfristig eine Herausforderung für die nachhaltige Gestaltung von Elektromobilitätssystemen dar.

Gegenwärtig ist die Reichweite von Elektrofahrzeugen im Vergleich zu konventionellen Verbrennerfahrzeugen eine knappe und kostbare Ressource. Es wird voraussichtlich noch einige Zeit dauern, bis man ein Elektrofahrzeug mit 600 km Reichweite zu vergleichbaren Kosten herstellen kann wie ein Verbrennerfahrzeug mit 600 km Reichweite. Auswertungen von Mobilitätsdaten zeigen zwar, dass ein substantieller Anteil der PKW durch Elektrofahrzeuge mit der heute üblichen Reichweite von circa 150 km ersetzbar wäre (Pearre, Kempton, Guensler, & Elango, 2011). Autokäufer tendieren allerdings weiter dazu eher größere Reichweiten zu bevorzugen (ADAC, 2013; Bunzeck, Feenstra, & Paucovic, 2011; Dimitropolous, Rietveld, & van Ommeren, 2013). Eine entscheidende Frage ist daher, wie die verfügbaren Batterieressourcen so effizient wie möglich in Mobilitätsressourcen für den Nutzer umgesetzt werden können, wie man den Nutzern also helfen kann mit der verfügbaren Batterietechnik die maximale nutzbare Reichweite zu erzielen.

Auch langfristig ist die effiziente Ausnutzung der Batterieressourcen durch den Nutzer ein entscheidender Faktor für den optimalen Nachhaltigkeitseffekt von Elektromobilitätssystemen. Denn während für den Nutzer die größtmögliche Reichweite den maximalen Nutzen bietet, ist aus Sicht der Nachhaltigkeit[4] die kleinste ausreichende (akzeptable) Batteriekapazität die optimale Auslegung, da die Batterieproduktion durch hohen Energiebedarf und Verwendung seltener natürlicher Ressourcen einen signifikanten Anteil am ökologischen Fußabdruck eines Elektrofahrzeugs hat (McManus, 2012).

[4] Der Begriff Nachhaltigkeit wird im Sinne des Drei-Säulen-Modells der nachhaltigen Entwicklung (UN General Assembly, 2005) verwendet.

Unabhängig von den technischen Möglichkeiten ist also stets ein effizienter Einsatz verfügbarer Batterieressourcen geboten. Auch während der Nutzung besteht das Ziel aus Sicht der Nachhaltigkeit darin, aus der verfügbaren Batteriekapazität die maximal mögliche Mobilität für den Nutzer zu generieren. Der letztendliche Umweltnutzen hängt also entscheidend davon ab, welche Systemauslegung (Reichweitenausstattung) präferiert wird und wie effizient die verfügbaren Batterieressourcen ausgenutzt werden. Um ein maximal nachhaltiges Elektromobilitätssystem zu gestalten, bedarf es daher einem genauen Verständnis des Nutzererlebens und -verhaltens (für eine ausführlichere Betrachtung zu dieser Perspektive siehe Franke, Bühler, et al., 2012).

2.3 Vorbefunde zum Reichweitenerleben und -verhalten

Zu Beginn des Forschungsprojekts „MINI E Berlin powered by Vattenfall", welches die Grundlage dieser Dissertation darstellt, existierten kaum wissenschaftliche Erkenntnisse zum Nutzererleben und -verhalten im Umgang mit der Reichweite von Elektrofahrzeugen. Die wenigen verfügbaren Quellen gaben Hinweise darauf, dass es für Nutzer wahrscheinlich schwierig ist, die verfügbaren Ressourcen in einem Elektromobilitätssystem optimal auszunutzen.

So fanden sich in vereinzelten Feldstudien Hinweise darauf, dass Elektrofahrzeugnutzer die vorhandene Reichweite nur zum Teil ausnutzen und längere Strecken vermeiden (Botsford & Szczepanek, 2009; Golob & Gould, 1998) sowie das Fahrzeug bereits bei relativ hohen Ladezuständen aufladen (Gärling, 2001). In Medienberichten (Rahim, 2010) und vereinzelt auch in wissenschaftlichen Publikationen (Tate, Harpster, & Savagian, 2009) wurde dabei immer wieder das Konzept der Reichweitenangst, eine andauernde Angst mit dem Elektrofahrzeug liegenzubleiben, als eine mögliche Ursache genannt, jedoch ohne stichhaltige empirische Befunde dafür anzuführen. Insgesamt wurde also das Reichweitenerleben in vorangegangenen Berichten am ehesten mit dem Konzept „Angst" charakterisiert. Auch zum Ladeverhalten als einer entscheidenden Facette des Umgangs mit der Reichweite gab es kaum Vorbefunde, welche über die reine Beschreibung des Verhaltens hinausgingen (siehe z.B. Gärling, 2001). Zum Thema Reichweitenpräferenzen existierten schließlich einige Studien, die zeigten, dass Autokäufer starke Präferenzen für hohe Reichweitenauslegungen haben (siehe z.B. zusammengefasst in Metaanalyse von Dimitropoulos et al., 2013). Diese Studien beziehen sich jedoch auf Präferenzen von Personen ohne praktische Erfahrung mit Elektrofahrzeugen, weshalb die Aussagekraft solcher Befunde von einigen Forschern infrage gestellt wurde (Kurani & Turrentine, 1994).

2.4 Forschungsziele der Dissertation

Aufgrund dieses Forschungsstandes ergaben sich folgende zentrale Forschungsziele:

(1) Das erste Ziel bestand darin, auf Basis der Vorbefunde und anhand übertragbarer, bewährter Theorien aus verwandten Teilgebieten der angewandten Psychologie, ein Modell zu entwickeln, welches psychologische Konzepte und Mechanismen für die Strukturierung des Reichweitenerlebens und -verhaltens einführt und damit Hypothesen über das Nutzererleben und -verhalten sowie über mögliche Einflussfaktoren ableitbar macht. Das Modell wurde über die Artikel 1-3 kontinuierlich entwickelt. Eine Synthese daraus findet sich in Abschnitt 4.

(2) Das zweite Ziel bestand darin, eine Methodik zu entwickeln, mit der man, unter den besonderen Bedingungen einer Feldstudie, die neu eingeführten psychologischen Konzepte und die Einflussfaktoren reliabel und valide erfassen kann. Neue Methodenentwicklungen sind insbesondere in den Artikeln 1 bis 3 dokumentiert (ein kurzer Überblick dazu findet sich in Abschnitt 5).

(3) Basierend auf diesen Werkzeugen bestand das dritte Forschungsziel darin, die Interaktion mit den Reichweitenressourcen in der Alltagsnutzung zu charakterisieren sowie die Zusammenhänge zwischen den aus der Theoriearbeit abgeleiteten Einflussfaktoren und der Interaktion mit der Reichweite zu testen. Letztendlich ging es darum, die Einflussfaktoren auf die Effizienz der Reichweitenausnutzung besser zu verstehen. Dieses Ziel wird zentral in den Artikeln 1 und 2 verfolgt.

(4) Das vierte Forschungsziel bestand darin, auch die andere Seite der Reichweiteninteraktion, also die Wiederherstellung von Reichweitenressourcen (das Ladeverhalten), besser zu verstehen. Auch hier ging es darum, Einflussvariablen auf das Ladeverhalten zu testen und Zusammenhänge zur nachhaltigen Interaktion mit dem Elektromobilitätssystem zu untersuchen (siehe Artikel 3).

(5) Um jenseits der direkten Interaktion mit der Reichweite während der Nutzung schließlich auch den Aspekt der nachhaltigen Auslegung von Elektromobilitätssystemen hinsichtlich der Reichweite abzudecken, bestand das fünfte Forschungsziel darin, die Präferenzen für bestimmte Ressourcenauslegungen (Reichweitenkonfigurationen) besser zu verstehen (siehe Artikel 4).

Die Motivation für diese Forschungsziele bestand darin, dass es durch ein besseres psychologisches Verständnis eventuell möglich werden könnte Maßnahmen abzuleiten, die zu einem besseren Nutzererleben, einer Vergrößerung der nutzbaren Ressourcen (also insgesamt zu einer besseren Nutzerfreundlichkeit) und einer nachhaltigeren Interaktion mit dem Elektromobilitätssystem beitragen können.

3 Der Umgang mit knappen Ressourcen

In der Interaktion mit unserer Umwelt sind wir täglich mit knappen Ressourcen konfrontiert. Dabei kommen wir durch Ressourcenverknappung oder Steigerung von Ressourcenanforderungen immer wieder in kritische Situationen, in denen sich ein (mögliches) Missverhältnis zwischen, einerseits, den sich aus der Umwelt ergebenden Ressourcen und Anforderungen und, andererseits, unseren individuellen Ressourcen und Zielen abzeichnet. Wie gehen wir mit solchen Situationen um, beziehungsweise wie vermeiden wir solche Situationen?

3.1 Das Task-Capability Interface (TCI) Modell

Im Bereich der Verkehrspsychologie zeigen sich solche Situationen beispielsweise bei der situationsspezifischen Entscheidung für ein bestimmtes sicherheitsbezogenes Fahrverhalten (z.B. Wahl von Geschwindigkeit oder Sicherheitsabstand). Im vielzitierten Artikel von Fuller (2005) stellt dieser das Task-Capability Interface Modell als eine Alternative zu verschiedenen vorangegangenen kontrolltheoretischen Ansätzen dar. Gemäß Fuller ist neben dem Hauptziel, dem Erreichen des Fahrtziels, die Vermeidung von Kollisionen ein zentrales Kriterium bei der Wahl eines bestimmten Fahrverhaltens. Als zentrales Wirkprinzip propagiert Fuller: „drivers adopt a level of task difficulty that they wish to experience when driving, and then drive so as to maintain it" (Fuller, 2005, S. 462). Im Gegensatz zu früheren Arbeiten, welche das Erleben von Angst (Taylor, 1964) und das Risikoerleben (Wilde, 1982) als Wirkprinzip sehen, ist hier also die erlebte Aufgabenschwierigkeit die entscheidende Heuristik für die Anpassung des Fahrverhaltens. Sie resultiert aus dem Verhältnis von Ressourcen (capabilities) und Aufgabenanforderungen (task demands).

Die Ressourcen ergeben sich aus drei Variablenklassen: Zunächst bestimmen biologische Charakteristika (z.B. Verarbeitungskapazität) und erworbene Charakteristika (Wissen und Fertigkeiten) die Kompetenz, also die maximal verfügbaren Ressourcen. Durch verschiedene weitere leistungsbestimmende Charakteristika (z.B. Einstellungen, Motivation, Anstrengung, Müdigkeit) sind die maximal verfügbaren Ressourcen jedoch selten vollständig zugänglich. Die Aufgabenanforderungen setzen sich ebenfalls aus verschiedenen Variablen zusammen (z.B. Umwelteinwirkungen, andere Verkehrsteilnehmer, Eigenschaften des Fahrzeugs, gewählte Geschwindigkeit). Fuller geht davon aus, dass ein bestimmtes Verhältnis beider Größen (eine bestimmte Aufgabenschwierigkeit) vom Fahrer präferiert wird. Dieses präferierte Verhältnis ist wiederum von individuellen Faktoren (z.B. Persönlichkeit) abhängig.

Während der Fahrt gleichen die Fahrer also kontinuierlich die wahrgenommene Aufgabenschwierigkeit mit der akzeptablen (präferierten) Aufgabenschwierigkeit ab, welche auf der

Einschätzung der gegenwärtig verfügbaren und zugänglichen Ressourcen fußt. Basierend auf diesem Abgleich kommt es dann gegebenenfalls zur Verhaltensanpassung. Fuller sieht hier die Erhöhung/Verringerung der Fahrgeschwindigkeit als zentrales Werkzeug. Dieses Modell deutet damit auf die vielfältigen individuellen und situationalen Faktoren hin, welche die Bewertung einer Fahrsituation (und damit das Fahrverhalten) beeinflussen und gibt damit Ansatzpunkte für eine Beeinflussung des Fahrverhaltens hin zu mehr Sicherheit.

3.2 Übertragbarkeit des TCI-Modells

Der Umgang mit der Reichweite eines Elektrofahrzeugs ist eine ähnliche psychologische Situation wie die Kontrolle des sicherheitsbezogenen Fahrverhaltens. Auch hier besteht das primäre Ziel darin, das Fahrtziel zu erreichen, während verschiedene sekundäre Ziele (z.B. Fahrkomfort, Fahrzeit) und die verfügbaren Ressourcen (Reichweitenressourcen und individuelle Ressourcen zur Reichweitenverlängerung) in Balance gehalten werden müssen. Es scheint plausibel, dass Fahrer beim Umgang mit der Reichweite ebenfalls nach einem bestimmten Gleichgewicht von Ressourcen und Anforderungen streben und dass die empfundene Aufgabenschwierigkeit von zahlreichen Faktoren abhängig ist. Auch scheint es plausibel, dass es ein maximales Potential bei den individuellen Ressourcen zur Reichweitenverlängerung gibt, welches durch verschiedene Einflussvariablen aber selten vollständig zur Verfügung steht.

Während bei der Kontrolle des sicherheitsbezogenen Fahrverhaltens jedoch die Geschwindigkeitswahl als primäres Werkzeug zur Kontrolle der Aufgabenschwierigkeit dient (Fuller 2005), hat dieser Faktor bei der Regulation der Reichweite eine geringere Bedeutung. Zwar ist die mittlere Geschwindigkeit ein wichtiger Faktor im Rahmen des sparsamen Fahrens (Verlängerung der Reichweite), allerdings neben vielen anderen Parametern der Geschwindigkeitsdynamik (z.B. Beschleunigungsintensität, Effizienz von Verzögerungsvorgängen) und weiteren Faktoren (z.B. Einsatz von Zusatzverbrauchern). Auch spielen bei der Kontrolle der Reichweitenressourcen strategische Entscheidungen vor der Fahrt eine viel größere Rolle (z.B. Ladeverhalten, Streckenwahl). Die Regulation findet also weniger stark auf der Kontroll- und Manöverebene (Michon, 1985) statt, sondern stärker auf der strategischen Ebene. Die Regulation auf dieser Ebene wird im Modell von Fuller (2005) allerdings nur am Rande betrachtet.

Auch ist die Rückmeldung zum Erfolg bestimmter Verhaltensweisen beim Umgang mit der Reichweite zeitlich stärker verzögert und bedarf einer komplexeren Verarbeitung. Während sich eine Fahrsituation durch eine Änderung der Geschwindigkeit innerhalb von Sekunden hinsichtlich der Schwierigkeit der Kollisionsvermeidung komplett ändern kann, werden Effekte von Aktionen auf die Reichweite typischerweise erst nach Minuten sichtbar. Während viele sicherheitskritische Elemente in der Fahrumgebung direkt sichtbar sind, müssen zur Kontrolle der Reichweitensituation viele nicht unmittelbar sichtbare Informationen integriert werden (z.B. Erinnerung des Streckenverlaufs, um die Reichweitenveränderung nachzuvollziehen, Annahmen über den weiteren Streckenverlauf notwendig, um Reichweitenveränderung vorherzusagen). Durch diese verstärkte Intransparenz kann es zu größerer Unsicherheit bei der Abschätzung der Kritikalität einer Situation kommen.

3.3 Das Comfort Zone Modell von Summala (2007)

Neben dem vielbeachteten Modell von Fuller (2005) besitzt das Modell von Summala (2007) einige Eigenschaften, die für die vorliegende Arbeit relevant scheinen. Grundlegend hat das Modell viele Ähnlichkeiten mit dem TCI-Modell (Fuller, 2011; Lewis-Evans, de Waard, & Brookhuis, 2013), weist dabei aber trotzdem einen spezifischen andersartigen Zugang auf (Lewis-Evans et al., 2013). Ähnlich wie bei Fuller (2005) ist ein Ausgangspunkt des Modells, dass Fahrer versuchen verschiedene Ziele zu verfolgen (z.B. Zeitdruck durch höhere Geschwindigkeit reduzieren, Fahrspaß steigern). Dabei wird dem Konzept der Aufgabenschwierigkeit das Konzept der Komfortzone entgegengesetzt. Als zentrale Kontrollvariablen werden hierbei die sogenannten safety margins (hier übersetzt als Sicherheitsgrenzen) vorgeschlagen. Diese werden als zeitlich-räumliche Distanzen operationalisiert (z.B. time to collision). Wenn eine solche Grenze/Zone verletzt wird, empfinden Fahrer dies als unangenehm. Fahrer versuchen daher die Überschreitung dieser Grenzen (Schwellenwerte) zu vermeiden und so in ihrer Komfortzone zu bleiben. Die Komfortzone kann also als ein gewisser schützenswerter Raum verstanden werden. Durch diesen Prozess kommt es im alltäglichen Fahrererleben wenig zu stark negativen emotionalen Zuständen (z.B. Angst; Summala, 2007).

3.4 Übertragbarkeit des Comfort Zone Modells

Die stärkere emotionale Orientierung des Modells von Summala (2007) scheint auf den ersten Blick besser auf das Erleben einer knappen Reichweite zu passen als das Modell von Fuller, auch wenn Summala davon ausgeht, dass stark negative Emotionen (z.B. Angst, also übertragen: Reichweitenangst) durch die Art der Kontrolle (immer in der Komfortzone bleiben) kaum vorkommen. Das Konzept der Sicherheitsgrenzen stellt darüber hinaus eine interessante Möglichkeit zur Operationalisierung dar, welche durch die räumliche Formulierung leichter auf den Umgang mit der Reichweite übertragbar scheint als das Konzept der Aufgabenschwierigkeit. Der Gedanke, dass es einen bestimmten schützenswerten Raum (die Komfortzone) gibt, bietet auch eine elegante Erklärung der in vorangegangenen Studien gefundenen Anzeichen für eine suboptimale Reichweitenausnutzung (siehe Abschnitt 2.3). Das Konzept der Komfortzone deutet damit auf eine mögliche alternative Konzeption für das Konzept Reichweitenangst hin.

Allerdings geht Summala (2007) davon aus, dass es für den Fahrer durch die schnelle Regulierbarkeit der Einhaltung bestimmter Sicherheitsgrenzen immer leicht ist in der Komfortzone zu bleiben. Die wiederholten Berichte über Reichweitenangst (siehe Abschnitt 2.3) passen eher nicht dazu. Es scheint daher sinnvoll noch einmal ein Modell zu konsultieren, welches sich stärker mit der Regulation knapper Ressourcen in kritischen Situationen beschäftigt und ein breiteres Anwendungsspektrum hat.

3.5 Das transaktionale Stressmodell

Das transaktionale Stressmodell von Lazarus und Folkman (1984) zählt zu den einflussreichsten psychologischen Modellen der letzen Jahrzehnte. Ähnlich wie das Modell von Fuller (2005) stellen Lazarus und Folkman (1984) heraus, dass die Erlebnisqualität einer Situation und damit auch das gezeigte Verhalten von vielen individuellen Faktoren abhängt. Dabei kommt es zu Stress, wenn sich ein *subjektiv wahrgenommenes* Missverhältnis zwischen den Ressourcen einer Person und den sich aus der Umwelt ergebenden Anforderungen einstellt. Stress ist damit: „A relationship between the person and the environment that is appraised by the person as taxing or exceeding his or her resources and endangering his or her well-being." (Lazarus & Folkman, 1984, S. 19).

Ähnlich wie Fuller (2005) gehen Lazarus und Folkman (1984) von einem kontinuierlichen zirkulären Prozess aus, über den diese Interaktion von Mensch und Umwelt reguliert wird. Dabei steht die Bewertung (appraisal) der Situation im Zentrum. Die primäre Bewertung ordnet ein bestimmtes Verhältnis mit der Umwelt in Bezug auf das eigene Wohlbefinden als irrelevant, positiv oder stressreich ein, wobei ein stressreiches Verhältnis als Schädigung/Verlust, Bedrohung oder Herausforderung bewertet wird. Es wird also eingeschätzt, inwieweit eine bestimmte Situation für ein Individuum kritisch ist, ob also eine Anpassung notwendig ist. Die sekundäre Bewertung beurteilt die Möglichkeiten das stressreiche Verhältnis mit der Umwelt durch Bewältigungsressourcen zu lösen. Es wird also eingeschätzt, welche Bewältigungsoptionen zur Verfügung stehen und ob man damit die notwendige Anpassung durchführen kann. Basierend auf diesen Bewertungen ergibt sich das Stresserleben einer Person.

Schließlich werden Anstrengungen unternommen, um Situationen zu bewältigen, in denen sich ein kritisches Verhältnis zwischen Anforderungen und Ressourcen abzeichnet. Hierbei gibt es meist verschiedene mögliche Bewältigungsstrategien. Damit spielen individuelle Bewältigungsstile eine substantielle Rolle dabei, wie (potentiell) stressreiche Situationen von einer Person gelöst werden. Durch das letztendlich gezeigte Bewältigungsverhalten und durch Umweltfaktoren ändert sich wiederum die Situation. Der Kreis schließt sich mit der Neubewertung (reappraisal) der Situation, die in ihrer Struktur der anfänglichen Bewertung entspricht (Lazarus & Folkman, 1984).

Personale Ressourcen können diesen Prozess beeinflussen und sind damit zentral für die Stressresistenz. Neben effektiven Bewältigungsstrategien stellen Lazarus und Folkman (1984) hier besonders bestimmte Überzeugungen (z.B. Kontrollüberzeugungen) als wirksamen Faktor heraus. Auch in der nachfolgenden Forschung wurden Bewältigungsstrategien, Persönlichkeitsmerkmale und soziale Unterstützung als wichtige Faktoren charakterisiert (Holahan & Moos, 1990).

3.6 Übertragbarkeit des transaktionalen Stressmodells

Eine Situation, in der Restreichweite kaum größer ist als die Reststrecke zum Fahrtziel, kann als Situation verstanden werden, in der man geringe Mobilitäts*ressourcen* hat, um Anforderungen aus der Umwelt, beziehungsweise eigenen Zielen, gerecht zu werden. Da die Reichweitenressourcen zum erheblichen Teil durch den Nutzer beeinflussbar sind, scheint auch der zirkuläre Prozess ein vielversprechendes Grundmodell darzustellen (man bewertet eine bestimmte Situation und die Handlungsoptionen um das Ressourcengleichgewicht wiederherzustellen, man wählt bestimmte Bewältigungsstrategien und kann später deren Wirksamkeit bewerten). Die von Lazarus angenommenen komplexeren Bewertungs- und Bewältigungsprozesse passen auch besser auf die Reichweiteninteraktion, welche auch einer komplexeren Einschätzung bedarf. Strukturell gibt es also Parallelen zwischen dem Erleben einer kritischen Reichweitensituation und dem Stresserleben in anderen Domänen.

Aber ist es wirklich plausibel anzunehmen, dass Elektrofahrzeugnutzer ständig Reichweitenstress (Reichweitenangst) erleben? Es ist eher anzunehmen, dass das Nutzererleben durch die Vermeidung von Reichweitenstress charakterisiert wird. Dass also, ähnlich wie in den Modellen von Fuller (2005) und Summala (2007), bestimmte präferierte Zielwerte (ein bestimmtes Verhältnis von Reichweitenressourcen und Reichweitebedürfnissen) angestrebt werden. Hierbei scheint besonders die Konzeption von Summala (2007) fruchtbar, dass Personen durch die Einhaltung bestimmter Sicherheitsgrenzen (bei Reichweite eher eindimensional: Sicherheitspuffer) in ihrer individuellen Komfortzone bleiben.

Hier ist es sinnvoll noch einmal zu betonen, dass alle drei Modelle auf dem gleichen Grundmodell basieren, nämlich auf kontrolltheoretischen Annahmen (Fuller, 2011; Leventhal, Halm, Horowitz, Leventhal, & Ozakinci, 2004). Es scheint daher angebracht, die Interaktion mit der Reichweite aus einer kontrolltheoretischen Perspektive zu betrachten und damit für ein besseres Verständnis der Reichweiteninteraktion auch generell Befunde zu Einflussfaktoren auf das Erleben und Verhalten aus der Forschung zum Thema Selbstregulation (Carver & Scheier, 2001) und Handlungsregulation (Frese & Zapf, 1994; Hacker, 2003) einzubeziehen (siehe z.B. Abschnitt 1.1 in Artikel 2).

4 Die adaptive Kontrolle von Reichweitenressourcen

Basierend auf den in Abschnitt 3 dargestellten Ansätzen, insbesondere basierend auf dem transaktionalen Stressmodell von Lazarus & Folkman (1984), wurde das Modell für diese Dissertation entwickelt: Das Modell der adaptiven Kontrolle von Reichweitenressourcen. Das Ziel war (siehe Forschungsziel 1, Abschnitt 2.4), psychologische Konzepte und Mechanismen für die Strukturierung des Reichweitenerlebens und -verhaltens einzuführen und damit Hypothesen über das Nutzererleben und -verhalten sowie über mögliche Einflussfaktoren ableitbar zu machen. Denn wenn man auf Basis einer psychologischen Theorie versteht, welche Faktoren und Mechanismen dazu führen, dass manche Nutzer besser mit der Reichweite zurechtkommen als andere (z.B. mehr Reichweitenausnutzung, weniger Reichweitenstress), was also die Herausforderungen in der Interaktion mit der Reichweite sind, dann kann man mit diesem Wissen möglicherweise ein Elektromobilitätssystem hin zu mehr Nutzerfreundlichkeit und Nachhaltigkeit gestalten. Das Modell wurde über die Artikel 1-3 weiterentwickelt. Der folgende Abschnitt stellt eine Synthese dieser Entwicklungen dar. Um die Darstellung kompakt zu halten, wird bei Detailaspekten auf den jeweiligen Abschnitt in den Artikeln verwiesen.

4.1 Psychologische Konzepte zum Umgang mit Reichweite

4.1.1 Reichweitenschwellen

Ein Ausganspunkt für die Entwicklung des Modells war die Beobachtung, dass die technisch verfügbare Reichweite für die Nutzer scheinbar nie vollständig nutzbar ist, es also zu einer suboptimalen Ausnutzung der Energieressourcen kommt. Aus dem Modell von Lazarus & Folkman (1984) geht hervor, dass eine physikalisch identische Situation eine grundverschiedene psychologische Situation für das Individuum darstellen kann. Beim Umgang mit Reichweitenressourcen werden vier Reichweitenschwellen vorgeschlagen, die den Übergang von der objektiven physikalischen Reichweitensituation (technisch mögliche Reichweite) zur subjektiven psychologischen Reichweitensituation (tatsächlich nutzbare Reichweite) charakterisieren:

(1) Die *technische* Reichweite (Fahrzyklusreichweite) ist die technisch mögliche Reichweite basierend auf einem standardisierten Fahrzyklus (siehe z.B. André, 2004). (2) Die *kompetente* Reichweite ist die maximal für einen Nutzer *erreichbare* Reichweite, basierend auf der Kompetenz zum sparsamen Fahren und dem erworbenen Systemwissen des Nutzers. (3) Die *performante* Reichweite ist die im Alltag (im Durchschnitt) tatsächlich *verfügbare* (angezeigte) Reichweite, basierend auf der Motivation und den Angewohnheiten bestimmtes (sparsames) Fahrverhalten zu zeigen. Es wird also wie bei Fuller (2005) davon ausgegangen, dass die maximal erreichbaren Ressourcen durch verschiedene

Variablen selten vollständig verfügbar sind. (4) Die *komfortable* Reichweite ist schließlich die tatsächlich mit einem guten Gefühl *nutzbare* Reichweite und kann damit auch als präferierter Reichweitensicherheitspuffer verstanden werden. Dies ähnelt den Konzepten Komfortzone und Sicherheitsgrenze von Summala (2007). Die komfortable Reichweite ist damit ein Weg, für das Konzept der Reichweitenangst ein besser operationalisierbares und psychologisch besser fundierbares Konstrukt zu finden.

Eine Kernannahme ist, dass die drei psychologischen Reichweitenschwellen (2-4) einer Reihe von psychologischen Einflussvariablen unterliegen, insbesondere denen aus der Forschung zu Stress und Selbstregulation bekannten Variablen (siehe im Detail die Ausführung in Artikel 1, Abschnitt 1.2; Artikel 2, Abschnitt 1.1.1 bis 1.1.3). Dies führt schließlich dazu, dass jeder Nutzer eine individuelle Effizienz bei der Reichweitenausnutzung zeigt. Hierbei wird angenommen, dass die individuellen Reichweitenschwellen aus einem Anpassungsprozess hervorgehen, in dem, wiederum basierend auf den Persönlichkeitseigenschaften, dem jeweils zum Zeitpunkt verfügbaren Wissen und den gemachten Erfahrungen, die Reichweitenschwellen verändert und gefestigt werden. Es wird also angenommen, dass die Reichweiten sowohl zwischen Personen als auch über die Zeit variieren. In Artikel 2 werden diese Schwellen noch einmal im Detail aus einer psychologischen Perspektive begründet (siehe Abschnitte 1.1.1 bis 1.1.3). Insgesamt deutet sich hier also an, dass typischerweise Diskrepanzen zwischen den psychologischen Reichweitenschwellen bestehen werden.

4.1.2 UBIS-Konzept

Neben der interindividuell unterschiedlichen Bewertung von Reichweitensituationen geht das Modell auch davon aus, dass es interindividuell unterschiedliche Präferenzen für bestimmte Bewältigungsstrategien gibt. Dies basiert auf der Annahme unterschiedlicher Bewältigungsstile im Modell von Lazarus und Folkman (1984), und auf der etablierten Annahme unterschiedlicher Fahrstile (Lajunen & Özkan 2011), welche auch in kontrolltheoretischen Modellen des sicherheitsbezogenen Fahrverhaltens eine Rolle spielen (Fuller, 2011).

Erste Anzeichen für unterschiedliche Bewältigungsstrategien beim Umgang mit knappen Batterieressourcen fanden sich in vorangegangenen Studien zum Ladeverhalten von Smartphone-Nutzern, welche ebenfalls mit relativ knappen Batterieressourcen auskommen müssen (Rahmati & Zhong, 2009). Basierend auf diesen Vorbefunden wurde das UBIS-Konzept (user-battery interaction style) in das Modell eingeführt. Die Annahme ist, dass der UBIS eines Nutzers Ausdruck einer präferierten Strategie zur Ressourcenoptimierung ist. Während Personen mit einem niedrigeren UBIS eher versuchen die Beanspruchung durch den häufigen Umgang mit den Energieressourcen zu minimieren, versuchen Personen mit einem hohen UBIS die durch häufiges Laden entstehenden

Anstrengungen zu vermeiden. Diese Präferenz für eine schwächere oder stärkere Interaktion mit den Batterieressourcen sollte sich auch im Verhalten niederschlagen (Laden, wenn sich die Gelegenheit ergibt versus Laden, wenn es subjektiv notwendig erscheint) sowie einen Einfluss auf die generelle Interaktion mit der Reichweite (z.B. Lernprozesse, Reichweitenausnutzung) haben. Das Konzept ist in Artikel 3 (Abschnitt 1.2) im Detail dargestellt.

4.2 Der Prozess der Reichweitenkontrolle

Der Umgang mit Reichweitenressourcen wird im Modell als Kontrollprozess verstanden. Hierbei werden bestimmte bevorzugte Zustände angestrebt (z.B. hinsichtlich der Restreichweite stets in der persönlichen Komfortzone bleiben), welche ihren Ausdruck in bestimmten Referenzwerten finden (z.B. individuelle komfortable Reichweite). Diese Referenzwerte werden wiederum von verschiedenen Faktoren (z.B. Persönlichkeitsfaktoren) beeinflusst. Letztendlich führt dieses Zusammenspiel zu einer bestimmten individuellen Effizienz in der Reichweitenausnutzung. Die grundlegende Annahme des Modells ist, dass Personen bei der Interaktion mit knappen Ressourcen kontinuierlich das Verhältnis (die Passung) von Mobilitätsbedürfnissen und Mobilitätsressourcen überwachen und steuern. Der Kontrollprozess ist in Abbildung 1 dargestellt.

Der Kontrollprozess beginnt damit, dass Nutzer ihre aktuellen Mobilitätsressourcen (z.B. verbleibende Reichweite, verfügbare Ladeoptionen) mit ihren Mobilitätsbedürfnissen (z.B. Distanz der nächsten geplanten Fahrt, aktuell verbleibende Reststrecke) abgleichen. Dies ergibt jeweils einen bestimmten wahrgenommenen verfügbaren Reichweitenpuffer. Dieser Puffer wird nun mit dem präferierten Sicherheitspuffer (komfortable Reichweite) abgeglichen (Bewertung der Reichweitensituation). Dieser Abgleich ähnelt der primären Bewertung bei Lazarus und Folkman (1984). Es gibt bei der Abschätzung des verfügbaren Reichweitenpuffers jedoch immer eine Unsicherheit, da sich die Reichweitensituation durch unerwartete Ereignisse oder ein verändertes Fahrverhalten stark ändern kann (Reichweite wird in der Regel auf Basis des vorangegangenen Fahrverhaltens berechnet; Rodgers & Zoepf, 2013). Hier ist es also notwendig, in der Bewertung der Reichweitensituation auch das Wissen zur performanten (z.B.: Ist die gegenwärtig angezeigte Reichweite eher über oder unter der üblicherweise verfügbaren Reichweite bei diesem Ladestand – in welche Richtung liegt also wahrscheinlich der Schätzfehler?) und kompetenten Reichweite (Kann ich die Reichweite unter den aktuellen Bedingungen noch erheblich ausdehnen?) einzubeziehen. Dies ähnelt der sekundären Bewertung bei Lazarus und Folkman (1984). Wenn der verfügbare Reichweitenpuffer wesentlich größer als der präferierte Reichweitensicherheitspuffer (komfortable Reichweite) ist, dann ist diese Bewertung ein schneller und automatischer Prozess (Ergebnis der primären Bewertung: unkritische Situation). Wenn sich jedoch nur eine kleine positive oder gar negative Differenz ergibt, oder eine größere Unsicherheit besteht (z.B. lange unbekannte Strecke, Umweltbedingungen), kommt es zu einer genaueren Abwägung (genaue sekundäre Bewertung).

Je kritischer die Diskrepanz am Ende bewertet wird, desto stärker kommt es zu Reichweitenstress. Je mehr Reichweitenstress, desto eher werden Bewältigungsstrategien angewendet, um den Stress zu reduzieren (bzw. einen stärkeren Stress zu vermeiden). Hierbei gibt es meist mehrere mögliche Optionen (z.B. sparsamer fahren, Fahrzeug nachladen). Ob jedoch eine Bewältigungsstrategie zur Anwendung kommt und welche Bewältigungsstrategie eingesetzt wird, ist neben der Intensität des Stresserlebens auch von den jeweils aktuell vorhandenen Gelegenheiten abhängig. So kommt es womöglich schon zu einer Verhaltensanpassung, obwohl die oben besprochene Diskrepanz noch kaum kritisch ist, wenn sich eine besonders günstige Gelegenheit bietet die Reichweitenressourcen zu verlängern oder wieder aufzufüllen. Schließlich wird hier, in Anlehnung an das Konzept der Bewältigungsstile (Lazarus & Folkman, 1984) und Fahrstile (Lajunen & Özkan, 2011), davon ausgegangen, dass Nutzer unterschiedliche Präferenzen haben, wann sie welche Bewältigungsstrategie einsetzen. Der UBIS beschreibt eine solche Bewältigungsstildimension. Am Ende dieses Regulationsprozesses steht das konkret gezeigte Verhalten. Die Rückmeldung aus der Umwelt (z.B. Entwicklung der Reichweite während der Fahrt) zeigt Nutzern schließlich den Erfolg der eingesetzten Bewältigungsstrategien und kann damit langfristig zu Lernprozessen im Umgang mit der Reichweite führen (z.B. Verbesserung von Bewältigungsfertigkeiten, Veränderung von Reichweitenschwellen).

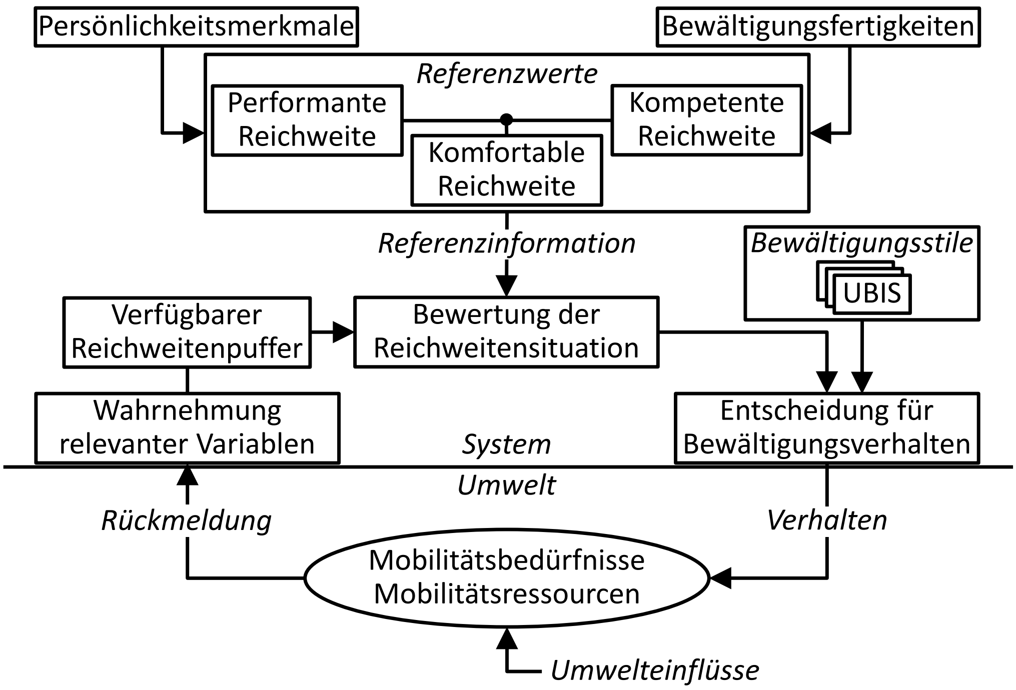

Abbildung 1. Der Prozess der adaptiven Kontrolle von Reichweitenressourcen.

5 Methodische Aspekte der Dissertation

Die Feldstudie „MINI E Berlin powered by Vattenfall“ bildete die Grundlage für diese Dissertation. In zwei sechsmonatigen Nutzungszeiträumen mit je 40 Nutzern wurden Daten zu drei Zeitpunkten erhoben: vor der Fahrzeugübergabe (T0), nach 3 Monaten (T1) und am Ende des Nutzungszeitraums nach 6 Monaten (T2). Die generelle Methodik der Feldstudie wurde bereits umfassend dargestellt (Bühler et al., 2010; Cocron et al., 2011; Franke, Bühler, et al., 2012; Krems et al., 2013). Die Methodenteile der 4 Artikel fassen die jeweils relevanten Aspekte zusammen. Hervorzuheben ist hier nur der Vergleich zwischen der Population deutscher Autofahrer und der Teilnehmerstichprobe, welcher nur in Artikel 4 (Abschnitt 3.2) berichtet wird. Für die Nachvollziehbarkeit der Ergebnisse sei hier zusammengefasst, dass sich Artikel 1 auf den Nutzungszeitraum 1, Artikel 2 auf den Nutzungszeitraum 2 und Artikel 3 und 4 auf die zusammengefassten Daten beider Nutzungszeiträume beziehen.

Entsprechend des Forschungsziels 2 (siehe Abschnitt 2.4) fanden für die Erfassung der relevanten Variablen für diese Dissertation verschiedene Erhebungsmethoden Verwendung: strukturierte qualitative Interviews (siehe Artikel 1), Fragebögen, experimentell orientierte Methoden (siehe „Reichweitenspiel“ im Folgeabsatz und Artikel 1), Tagebuchverfahren (Wege- und Ladetagebücher, siehe Artikel 1-4), und Loggerdaten aus den Fahrzeugen (siehe Artikel 2-3) sowie aus der Ladeinfrastruktur (siehe Artikel 3). Im Folgenden werden zentrale methodische Entwicklungen im Rahmen dieser Dissertation kurz zusammengefasst. In Abschnitt 6.4 folgt dann eine abschließende kritische Reflexion der Methodik.

Zur Erfassung der Reichweitenschwellen wurden verschiedene Operationalisierungen entwickelt. Das Reichweitenspiel stellt dabei das Herzstück zur Erfassung der komfortablen Reichweite dar. Die Bezeichnung dieses Instruments soll die angenommene Ähnlichkeit zwischen den Unsicherheitsfaktoren im Umgang mit der Reichweite und der Unsicherheit bei Aufgaben mit Glücksspielcharakter in der Forschung zu Entscheidung unter Unsicherheit (Hastie & Dawes, 2009) widerspiegeln. Der Grundgedanke bei der Konzeption bestand darin, dass es eventuell zu größeren Messfehlern führen könnte, wenn die Teilnehmer die Reichweitensituation zu einem bestimmten Gefühl („Diese Situation ist mir noch angenehm.“) mit Angabe numerischer Kilometerwerte definieren müssen. Besser könnte es sein, das Erleben bestimmter Reichweitensituationen zu erfassen und dann aus der Änderung des Erlebens mit Steigerung der Kritikalität der Reichweitensituation die komfortable Reichweite zu bestimmen (also: Ab welcher Differenz von Restreichweite und Restfahrstrecke ist es für den Nutzer nicht mehr komplett angenehm.). Die genaue Methodik hierzu ist in Artikel 1 (Abschnitt 2.5.1) dargestellt. Zur Erfassung der performanten und kompetenten Reichweite wurden jeweils Ansätze entwickelt, die zum Ziel hatten, ein möglichst umfassendes Bild dieser Reichweitenschwellen zu erheben. Hierfür wurden Befragungsdaten (erinnerte/geschätzte Werte) mit den Loggerdaten aus den Fahrzeugen (hohe Auflösung und Präzision der Werte) kombiniert. Die Herausforderung bestand hier insbesondere in der Vorverarbeitung der Loggerdaten (z.B. eindeutige Zuordnung von Datenpunkten zu bestimmten Nutzern, Behandlung von Störeinflüssen wie z.B. Temperaturschwankungen). Die Vorgehensweise hierzu ist in Artikel 2 (Abschnitt 2.5.1) dargestellt.

Für die Erfassung des ladebezogenen UBIS wurde in Artikel 3 eine Skala mit acht Items und ein paralleles Einzelitemmaß entwickelt und getestet. Obwohl eine Phase der Itemselektion in der Skalenentwicklung durch die Gegebenheiten in der Feldstudie nicht möglich war, konnten akzeptable Skaleneigenschaften erreicht werden. Die Skalenbeschreibung findet sich in Artikel 3 (Abschnitt 2.3.2). Zur Erfassung des Ladeverhaltens wurden neben einem Ladetagebuch auch Loggerdaten aus den Fahrzeugen herangezogen. Die Herausforderungen bestanden hier wiederum in der eindeutigen Zuordnung von Datenpunkten zu bestimmten Nutzern und in der sicheren Identifikation von Ladevorgängen, da diese durch eine Veränderung des Ladestandes diagnostiziert wurden und damit eine Abgrenzung von anderweitig bedingten Zuwächsen im Ladestand notwendig war (siehe Beschreibung in Artikel 3, Abschnitt 2.3.3).

6 Diskussion und Implikationen

6.1 Zusammenfassung der Befunde

Die zentralen Befunde zu den Forschungszielen 3 bis 5 (siehe Abschnitt 2.4) werden in den Artikeln jeweils im Diskussionsteil zusammengefasst. Zu Forschungsziel 3 findet sich die Zusammenfassung in Artikel 2 (erste 2 Absätze in Abschnitt 4) und in Artikel 1 (erster Unterabschnitt in Abschnitt 4). Zu Forschungsziel 4 findet sich die Zusammenfassung in Artikel 3 (Abschnitt 4.1) und zu Forschungsziel 5 findet sich die Zusammenfassung in Artikel 4 (erster Absatz in Abschnitt 5). Im Folgeabsatz werden noch einmal einige Kernbefunde knapp umrissen. In den folgenden Abschnitten werden die Befunde jeweils aus der Perspektive ihrer theoretischen (6.2) und praktischen (6.3) Implikationen betrachtet.

Bei einer durchschnittlichen Tagesfahrleistung mit dem Elektrofahrzeug von 38 km an Werktagen (Artikel 3) empfanden rund 90% der Nutzer die Reichweite als ausreichend für den Alltag (Artikel 1 und 2). Stressreiche Situationen gab es nur rund einmal pro Monat. Es gab eine große interindividuelle Varianz in der komfortablen Reichweite. Im Mittel waren die Nutzer lediglich bereit rund 75-80% der tatsächlich verfügbaren Reichweite auszunutzen. Es gab also substantielle Reichweitensicherheitspuffer. Als stressreduzierend bekannte Persönlichkeitsmerkmale (Kontrollüberzeugungen, Ambiguitätstoleranz) und Bewältigungsfertigkeiten (tägliche Übung, subjektive Kompetenz) waren auch mit einer hohen komfortablen Reichweite assoziiert (Artikel 1). Bis auf den Effekt der Ambiguitätstoleranz wurde dieses Befundmuster in Artikel 2 repliziert. Weiterhin wurden erwartete Zusammenhänge zwischen sportlichem Fahrstil und performanter Reichweite sowie zwischen Vorwissen/Übung und kompetenter Reichweite gefunden (Artikel 2). Die komfortable Reichweite stand mit der Reichweitenzufriedenheit im Zusammenhang. Im Durchschnitt gab es drei Ladevorgänge pro Woche, wobei bei Ladebeginn meist noch eine erhebliche Restreichweite verfügbar war (Artikel 3). Der UBIS zeigte sich als zeitlich relativ stabil und über verschiedene Geräte hinweg relativ konsistent und stand erwartungsgemäß mit bestimmten Mustern im Ladeverhalten in Zusammenhang. Der UBIS und die komfortable Reichweite konnten zusammen 37% der Varianz im typischen Batteriestand zu Ladebeginn aufklären. Ein hoher UBIS war mit einer größeren Reichweitenausnutzung und einer sichereren Schätzung der Reichweite unter verschiedenen Bedingungen assoziiert (Artikel 3). Die Reichweitenpräferenzen waren gegenüber den maximalen Tageswegstrecken in einer typischen Woche nicht übertrieben hoch (Artikel 4). Mit zunehmender Elektrofahrzeugerfahrung verringerten sich die Reichweitenpräferenzen und der Zusammenhang zwischen Mobilitätsbedürfnissen und Reichweitenpräferenzen verstärkte sich. Erlebte Reichweitenangst war mit höheren Reichweitenpräferenzen assoziiert.

6.2 Theoretische Implikationen

Bei der Interpretation der theoretischen Implikationen ist zu beachten, dass die Schlussfolgerungen teilweise auf indirekten Indikatoren fußen und der korrelative Feldstudienansatz kausale Schlussfolgerungen schwierig macht. Die Schlussfolgerungen sollten entsprechend betrachtet werden.

6.2.1 Reichweitenstress und Reichweitenregulation

Wie im Modell (siehe Abschnitt 4) konzipiert, zeigt sich, dass es selten zum Erleben stressiger Reichweitensituationen kommt (siehe Artikel 1, Abschnitt 3.2; Artikel 2, Abschnitt 3.1). Scheinbar ist es also für die Nutzer im Alltag möglich, das Verhältnis von Reichweitenressourcen und Mobilitätbedürfnissen erfolgreich zu regulieren. Dass es für die meisten Nutzer trotzdem vereinzelt zu kritischen Reichweitensituationen kommt und dass die Nutzer sich im Vergleich zum Verbrennerfahrzeug deutlich mehr Sorgen um die Reichweite machen (siehe Artikel 1, Abschnitt 3.2), deutet darauf hin, dass diese Regulation jedoch durchaus anspruchsvoll ist. Weiterhin deuten die Ergebnisse der qualitativen Analyse (siehe Artikel 1, Abschnitt 3.1) darauf hin, dass Nutzer den Umgang mit der Reichweite eher als Problemlöseaufgabe und weniger als stressreiche Interaktion erleben. Insgesamt bestätigt sich die Annahme, dass der Umgang mit knappen Ressourcen eher nicht vom Erleben sondern vom aktiven Vermeiden von Ressourcenkonflikten (stressreichen Situationen) gekennzeichnet ist. Wichtig ist, dass sich diese Ergebnisse auf Nutzer beziehen, die mit dem Elektrofahrzeug an Werktagen durchschnittlich eine Tagesfahrstrecke zurücklegen (38 km, siehe Artikel 3, Abschnitt 3.2), die der durchschnittlichen Tageswegstrecke in Deutschland (39 km; infas & DLR, 2010), beziehungsweise der Fahrleistung von vergleichbaren Verbrennerfahrzeugen ungefähr entspricht (circa 43 km; Ramsbrock, Vilimek, & Weber, 2013; Vilimek, Keinath, & Schwalm, 2012).

6.2.2 Subjektivität des Reichweitenerlebens

Darüber hinaus gibt es, wie im Modell konzipiert, eine große interindividuelle Varianz bezüglich der komfortablen Reichweite (siehe Artikel 1, Abschnitt 3.2; Artikel 2, Abschnitt 3.1). Da für die Erhebung dieser Variable standardisierte Reichweitensituationen genutzt wurden, kann hier geschlussfolgert werden, dass das Erleben einer Reichweitensituation tatsächlich sehr subjektiv ist und demnach nur zum Teil von den objektiven Gegebenheiten abhängig ist. Darin zeigt sich die im Modell konzipierte Parallele zum transaktionalen Stressmodell von Lazarus und Folkman (1984) deutlich.

Auch die gefundenen Zusammenhänge zwischen den Reichweitenschwellen und den aus der Literatur abgeleiteten Faktoren aus den Bereichen Persönlichkeit und Bewältigungsfertigkeiten (siehe Artikel 1, Abschnitt 3.3; Artikel 2, Abschnitt 3.2 und 3.3) stützen die analoge Betrachtung der

Regulation der Reichweite und der Regulation in potentiell stressreichen Situationen. So ist beispielsweise der besonders deutlich hervortretende Zusammenhang zwischen Kontrollüberzeugungen und komfortabler Reichweite analog zum besonders zentralen Zusammenhang von Kontrollüberzeugungen und Stressresistenz im Modell von Lazarus und Folkman (1984).

6.2.3 Reichweitenzufriedenheit und Reichweitenverhalten

Die im Modell angenommene zentrale Rolle der komfortablen Reichweite für die Bewertung der Reichweitensituation drückt sich auch darin aus, dass nur diese und nicht die anderen Reichweitenschwellen einen signifikanten Zusammenhang mit der Reichweitenzufriedenheit der Nutzer zeigt (siehe Artikel 2, Abschnitt 3.4). Nutzer, die also eine stärkere Stressresistenz bezüglich der objektiven Kritikalität von Reichweitensituationen haben, sind auch allgemein zufriedener mit der Reichweite. Schließlich zeigt sich auch, dass die komfortable Reichweite (der präferierte Sicherheitspuffer) mit der tatsächlichen Reichweitenausnutzung in Zusammenhang steht (Zusammenhang zum typischen Ladestand bei Aufladung siehe Artikel 3, Abschnitt 3.5; bzw. zum Indikator „Reichweitenausnutzung" aus Artikel 3: $r = .41$, $p = .001$, $n = 73$, Auswertung nicht im Artikel enthalten). Die komfortable Reichweite scheint also tatsächlich die Ressourcen zu definieren, die für den Nutzer wirklich nutzbar sind.

Auch der UBIS zeigt sich neben den Reichweitenschwellen als fruchtbares Konzept für das Verständnis der Reichweiteninteraktion. Mit Hinzunahme dieser Variable kann das Modell das typische Ladeverhalten der Nutzer bezüglich des Ladestandes zu Beginn des Ladevorgangs zu einem bedeutsamen Teil aufklären (37% der Varianz lassen sich durch UBIS und komfortable Reichweite aufklären, siehe Artikel 3, Abschnitt 3.5). Damit kann das Modell die Regulation der Reichweite hinsichtlich dieses Aspekts bereits relativ gut abbilden. Die in der Analyse sichtbare geringe Überlappung der beiden Variablen bei der Erklärung des Ladeverhaltens deutet auch an, dass die komfortable Reichweite und der UBIS wahrscheinlich zwei relativ unabhängige Konstrukte sind, welche den Kontrollprozess an verschiedenen Stellen beeinflussen (Bewertung der Situation versus Wahl der Bewältigungsstrategie).

6.2.4 Anpassungsprozesse über die Zeit

Auch wenn sich die vorliegende Dissertation primär mit den Regulationsprozessen auf zeitlicher Ebene einer Fahrt, beziehungsweise eines Ladevorgangs beschäftigt, macht das Modell auch Aussagen zu Anpassungsprozessen über einen längeren Zeitraum. Dies betrifft insbesondere die Annahme, dass die Reichweitenschwellen im Umgang mit der Reichweite erlernt werden (siehe

Abschnitt 4.1.1 und Artikel 1, Abschnitt 1.1). Dies begründet sich unter anderem auch darin, dass ein Einfluss von Wissen und Fertigkeiten (Bewältigungsfertigkeiten) auf die Reichweitenschwellen angenommen wird (durch Befunde gestützt, siehe Artikel 1, Abschnitt 3.3; Artikel 2, Abschnitt 3.3) und diese Kompetenzen teilweise erst in der Interaktion mit der Reichweite erlernt werden können. Tatsächlich findet sich, wie im Modell angenommen, eine Zunahme der komfortablen Reichweite über die ersten 3 Monate der Nutzung (Franke, Cocron, et al., 2012), und die Daten deuten darauf hin, dass sich der größte Teil der Anpassung hinsichtlich der verfügbaren/erreichbaren (performanten/kompetenten) Reichweite in den ersten 3 Monaten abspielt (Pichelmann et al., 2013). Wieder finden sich Variablen, welche mit einem besseren/schnelleren Anpassungsprozess in Zusammenhang stehen (Franke, Cocron, et al., 2012; Pichelmann et al., 2013). Es drängt sich also der Schluss auf, dass die interindividuellen Differenzen in den Reichweitenschwellen zum Teil das Ergebnis unterschiedlicher Anpassungsprozesse sind.

6.2.5 Weitere Forschung zum Modell der Reichweitenkontrolle

Viele Aspekte des Modells der adaptiven Kontrolle von Reichweitenressourcen bleiben im Rahmen dieser Dissertation zunächst unbetrachtet. Dies betrifft zum Beispiel die Wahrnehmung der Reichweite. Das Modell impliziert beispielsweise, dass eine kritischere Reichweitensituation mit einer stärkeren Auseinandersetzung mit den relevanten Variablen aus der Umwelt einhergehen sollte (erhöhte Aufmerksamkeit, genauere Wahrnehmung, umfassendere Verarbeitung). Hier wäre also zu testen, ob es mit Abnahme des verfügbaren Reichweitenpuffers tatsächlich zu einer stärkeren Aufmerksamkeit auf Reichweiteninformationen (z.B. Blickhäufigkeit) kommt, beziehungsweise ob mit höheren Reichweitenanforderungen (z.B. Vielfahrer/Wenigfahrer) auch eine genauere/intensivere Verarbeitung von verfügbaren Reichweiteninformationen einhergeht (z.B. höhere kognitive Verfügbarkeit von üblichen angezeigten Reichweitenwerten).

Ein weiterer Aspekt im Zusammenhang mit der Wahrnehmung ist, dass sich das Modell bisher nur auf zwei wesentliche Umweltvariablen konzentriert (Fahrstrecke und Reichweite). Durch die klare Messbarkeit ist dies zunächst auch eine Stärke des Modells, ähnlich wie sich Fuller (2005) auf die Geschwindigkeitswahl als regulierende Variable konzentriert, obwohl auch viele andere Faktoren denkbar sind. Inwieweit diese Vereinfachung jedoch das tatsächliche Erleben und Verhalten abbilden kann, oder weitere zentrale Situations-/Umweltvariablen (z.B. Dringlichkeit einer Fahrt, Fahrzweck) einbezogen werden müssten, ist eine Frage für die nachfolgende Forschung.

Schließlich ist in der Dissertation nur ein spezifischer Interaktionsstil (ladebezogener UBIS) untersucht worden. Es gibt aber noch weit mehr Handlungsmöglichkeiten, um eine kritische Reichweitensituation wieder aufzulösen beziehungsweise die Reichweite zu regulieren. Die Änderung des Fahrverhaltens (auf strategischer Ebene, Manöverebene oder Kontrollebene (Michon, 1985) ist ein weiterer Bereich in dem es verschiedene Interaktionsstile geben könnte. Beispielsweise bei unsicheren Reichweitensituationen erst durch stark sparsames Fahren Ressourcen „ansparen" und später gegebenenfalls wieder komfortorientierter fahren (in Analogie zum Bremsverhalten: „degressives" sparsames Fahren) versus mit steigender Kritikalität der Reichweitensituation kontinuierlich sparsamer fahren („progressives" sparsames Fahren).

6.2.6 Übertragbarkeit des Modells der Reichweitenkontrolle

Es stellt sich auch die Frage, ob das Reichweitenerleben in einem Elektrofahrzeug überhaupt grundlegend anders ist als in einem Verbrennerfahrzeug. Auch bei Verbrennerfahrzeugen können sich kritische Reichweitensituationen ergeben, allerdings sind diese durch die große Gesamtreichweite und das dichte Netz an einfach zugänglichen Möglichkeiten den Tank in wenigen Minuten wieder aufzufüllen viel leichter zu vermeiden. Die Regulation von Reichweitenressourcen spielt damit bei Verbrennerfahrzeugen eine viel geringere Rolle, denn in der Regel reicht es hier beispielsweise in jeder Situation auf das Aufleuchten der Reserveleuchte zu warten und dann eine der nächsten Tankstellen anzusteuern. Eine planende Interaktion mit den Ressourcen und ein Abgleich von Ressourcen und Anforderungen sind damit nur selten erforderlich. Es kann also angenommen werden, dass die psychologischen Prozesse im Umgang mit einer kritischen Reichweitensituation beim Verbrennerfahrzeug denen bei der Nutzung eines Elektrofahrzeugs ähneln (z.B. präferierter Sicherheitspuffer), dass also das Modell der Reichweitenkontrolle auch auf solche Fahrzeuge übertragbar ist. Die praktische Relevanz der Übertragung des Modells scheint jedoch gering.

Insgesamt ist das Modell möglicherweise auf verschiedene Situationen übertragbar in denen Menschen mit knappen energetischen Ressourcen in einem Mensch-Technik-System konfrontiert sind. Denn was macht die Ressourcensituation in einem Elektrofahrzeug aus? Die Aufrechterhaltung der Mobilität (Fahrziel erreichen, Erschöpfung von Ressourcen vermeiden) ist das Hauptziel, während durch die Nutzung des technischen Systems kontinuierlich Ressourcen verbraucht werden. Der Ressourcenspeicher ist dabei begrenzt und kann nur unter Investition anderer Ressourcen (z.B. Zeitressourcen) wieder gefüllt werden. Es bieten sich dabei nur periodisch günstige Möglichkeiten die Ressourcen wieder aufzufüllen. Diese Beschreibung der Ressourcensituation passt auf viele batteriebetriebene mobile Gerät (z.B. Handys) oder auch andere Systeme mit begrenzten Speichern für energetische Ressourcen. Damit kann das Modell möglicherweise auf viele weitere Anwendungskontexte übertragen werden.

6.3 Implikationen für die Anwendung

6.3.1 Elektromobilität mit begrenzter Reichweite ist alltagstauglich

Eine grundlegende Implikation aus der vorliegenden Dissertation ist, dass Elektromobilität bereits mit einem Fahrzeug mit rund 150 km im Alltag verfügbarer Reichweite alltagstauglich sein kann. Die Nutzer empfanden die Reichweite als eine Ressource, an die man sich anpassen kann (Artikel 1, Abschnitt 3.1). Nach einer Anpassungszeit von 3 Monaten zeigte sich eine hohe Reichweitenzufriedenheit und es kam nur selten zu stressreichen Reichweitensituationen (Artikel 1, Abschnitt 3.2; Artikel 2, Abschnitt 3.1). Der Begriff Reichweitenangst scheint also eher nicht für eine Charakterisierung des Reichweitenerlebens in der Alltagsnutzung geeignet zu sein. Schließlich waren auch die Reichweitenpräferenzen gegenüber den Mobilitätsbedürfnissen eher nicht überzogen (siehe Artikel 4, Abschnitt 4.1).

Wichtig ist, dass sich diese Ergebnisse auf Nutzer beziehen, die mit dem Elektrofahrzeug an Werktagen durchschnittlich eine Tagesfahrstrecke zurücklegen (38 km, siehe Artikel 3, Abschnitt 3.2), die der durchschnittlichen Tageswegstrecke in Deutschland (39 km; infas & DLR; 2010), beziehungsweise der Fahrleistung von vergleichbaren Verbrennerfahrzeugen ungefähr entspricht (circa 43 km; Ramsbrock et al., 2013; Vilimek et al., 2012). Diese Schlussfolgerung lässt sich also wahrscheinlich auf eine Reihe von typischen Nutzungskontexten übertragen. Es ist jedoch auch zu bedenken, dass sich die Ergebnisse auf eine Stichprobe von Early Adoptern beziehen (siehe Abschnitt 6.4.1), die tendenziell wahrscheinlich eine höhere Reichweitenzufriedenheit erzielen, da sie eher bereit (bzw. fähig) sind Nutzungsbarrieren zu akzeptieren (bzw. zu überwinden).

6.3.2 Praktische Erfahrung ist ein Wirkfaktor für Reichweitenakzeptanz

Wie bereits erwähnt (siehe Abschnitt 6.2.4), geben die Befunde Hinweise darauf, dass es beim Umgang mit der Reichweite zu Anpassungsprozessen kommt. Mit zunehmender Erfahrung nehmen die Reichweitenpräferenzen ab (siehe Artikel 4, Abschnitt 4.6) und die komfortable Reichweite nimmt zu (Franke, Cocron, et al., 2012). Es scheint, dass der wesentliche Teil der Anpassung an die Reichweite in den ersten 3 Monaten abgeschlossen ist (Pichelmann et al., 2013). Praktische Erfahrung ist also scheinbar der Schlüssel zu einer höheren Akzeptanz kleinerer Reichweitenauslegungen und einem besseren Nutzererleben. Für einen breiten Erfolg von Elektrofahrzeugen sollten potentielle Käufer daher eine günstige Möglichkeit haben ein Elektrofahrzeug über einen ausreichend langen Zeitraum zu testen. In Bezug auf die Akzeptanz kleinerer Reichweitenauslegungen hat jedoch auch eine einfacher realisierbare simulierte Erfahrung (Protokollierung und Exploration der Mobilitätsbedürfnisse) möglicherweise ein gewisses Potential.

Die Befunde zu den Einflussvariablen auf das Reichweitenerleben und -verhalten deuten jedoch auch darauf hin, dass bestimmte Nutzer einen größeren Anpassungserfolg haben als andere. Die Sammlung praktischer Erfahrung sollte daher möglichst über verschiedene Kanäle (z.B. Informations- und Assistenzsysteme im Fahrzeug und auf Smartphones, intensivere fachliche Kundenbetreuung in der Anfangszeit) unterstützt werden, um den Anpassungserfolg zu steigern und möglicherweise auch die Anpassungszeit zu verkürzen (den Lernprozess zu beschleunigen), also die Effektivität und Effizienz des Anpassungsprozesses zu fördern (siehe Abschnitt 6.3.4).

6.3.3 Suboptimale Reichweitenausnutzung ist eine Herausforderung

Auch nach der Anpassungszeit deuten die Daten jedoch darauf hin, dass die Nutzer im Alltag durchschnittlich lediglich 75-80% der für sie verfügbaren Reichweite mit einem guten Gefühl ausnutzen (siehe Artikel 2, Abschnitt 3.1; Artikel 1, Abschnitt 3.2), dass also 20-25% der wertvollen Reichweitenressourcen als psychologischer Sicherheitspuffer verlorengehen. Damit sind objektiv noch in der Reichweite liegende Fahrten nicht möglich und die Nutzer müssen häufiger ihr Verhalten an die Reichweite anpassen (z.B. nachladen) als eigentlich notwendig (siehe Artikel 1, Abschnitt 3.1). Es scheint also für die Nutzer schwierig wirklich nachhaltig (siehe Abschnitt 2.2) mit der Reichweite zu interagieren und eine hohe nutzbare Reichweite (große Komfortzone) zu erzielen. Demnach muss die Nutzerfreundlichkeit des technischen Systems verbessert werden (siehe Abschnitt 6.3.5) und die Effektivität und Effizienz des Anpassungsprozesses an die Reichweite gefördert werden (siehe Abschnitt 6.3.4).

6.3.4 Unterstützung von Anpassungsprozessen

Eine stärkere Tendenz die Reichweite aktiv auszureizen steht mit einem größeren Zuwachs an komfortabler Reichweite in Zusammenhang (Franke, Cocron, et al., 2012). Auch geht eine stärkere tägliche Interaktion mit der Reichweite (tägliche Übung) mit einer höheren komfortablen und kompetenten Reichweite einher (siehe Artikel 2, Abschnitt 3.3; Artikel 1, Abschnitt 3.3). Schließlich steht auch eine generelle Präferenz für kognitiv herausfordernde Aufgaben (Need for Cognition) tendenziell mit einer höheren komfortablen und kompetenten Reichweite (siehe Artikel 2, Abschnitt 3.2) und einem schnelleren Lernprozess (Pichelmann et al., 2013) in Zusammenhang. Die aktive und kontinuierliche Auseinandersetzung mit der Reichweite und die kritische Reflexion der Reichweitendynamik stellen scheinbar Voraussetzungen für einen erfolgreichen und schnellen Anpassungsprozess dar.

Die Nutzer sollten also, beispielsweise durch die Gestaltung von Informations- und Assistenzsystemen, kontinuierlich dazu angeregt werden, sich intensiv mit der Reichweite auseinanderzusetzen und die Reichweite aktiv zu explorieren. Hier bieten sich Ansätze aus dem Bereich der Gamification an, wie sie zum Beispiel bei Hybridfahrzeugen in Ansätzen schon zum Einsatz kommen (Pegoraro, 2012), also bestimmte Arten verstärkender (motivierender) Rückmeldung und gegebenenfalls auch spielerische Wettbewerbselemente. Gamification ist auch deswegen ein interessanter Ansatz, weil die vorliegende Arbeit zeigt, dass es zentral auf die *subjektive* Kompetenz im Umgang mit der Reichweite ankommt und das Reichweitenerleben insgesamt eine stark subjektive Angelegenheit ist. Je mehr also die Interaktion mit der Reichweite mit positiven Affekten assoziiert wird, desto eher ist man möglicherweise bereit, eine gewisse Beanspruchung durch die Interaktion mit der Reichweite zu akzeptieren (siehe z.B. auch Hassenzahl, 2001).

Ein solches System sollte aber primär darauf zielen, dass Nutzer ein akkurates mentales Modell über die Reichweitendynamik aufbauen (unter welchen Bedingungen ist welche Reichweite verfügbar/erreichbar). Dies sollte dazu führen, Unsicherheiten bei der Interpretation der Reichweite zu reduzieren, Vertrauen zum technischen System der Reichweitenvorhersage und -kontrolle zu entwickeln und in kritischen Situationen Handlungsoptionen direkt verfügbar zu haben und deren Wirksamkeit einschätzen zu können. Denn die Unsicherheit scheint ein zentrales Problem für die Nutzer zu sein (siehe Artikel 1, Abschnitt 3.1). In einem optimalen Fall erleben Fahrer auch zumindest einmal in einer geschützten Umgebung (z.B. begleitete Probefahrt) eine Situation mit einer Restreichweite nahe 0 km, um die psychologische Unsicherheit in Bezug auf das Fahrzeugverhalten im Grenzbereich der Reichweite abzubauen. All diese Maßnahmen könnten dazu beitragen, die Komfortzone in Bezug auf die Reichweite zu erweitern und Sicherheitspuffer zu reduzieren.

Wichtig scheint auch eine präzise und prominent platzierte Anzeige von Informationen zu Ladestand und Reichweite. Denn eine stärkere Interaktion mit den Batterieressourcen bei der Ladeentscheidung (höherer UBIS-Wert) steht mit einer besseren Reichweiteninteraktion und einer sichereren Abschätzung der Reichweitendynamik in Zusammenhang (siehe Artikel 3, Abschnitt 3.6). Die vorangegangene Forschung (Rahmati & Zhong, 2009) berichtet Hinweise darauf, dass eine präzise Anzeige eine Voraussetzung für die Ausbildung eines hohen UBIS (also einer starken Interaktion mit Batterieressourcen) in einem bestimmten Mensch-Technik-System ist.

Der Zusammenhang des Vorwissens am Beginn der Elektrofahrzeugnutzung mit der kompetenten Reichweite nach 3 Monaten Fahrzeugnutzung deutet darüber hinaus darauf hin, dass für einen selbstregulierten Lernprozess ein gewisses Hintergrundwissen hilfreich sein kann. Dieses sollte also direkt bei der Fahrzeugübergabe/Probefahrt und unterstützend auch in der ersten Nutzungszeit vermittelt und gefestigt werden. Insgesamt deutet das Befundmuster in dieser Dissertation darauf hin, dass besonders die ersten Monate der Elektrofahrzeugnutzung in Bezug auf den Umgang mit der

Reichweite für die Nutzer eine Herausforderung, und damit eine kritische Phase, darstellen können. Ein Elektromobilitätssystem sollte daher so gestaltet sein, dass es den Nutzer besonders in dieser Anpassungsphase unterstützt, beispielsweise durch die Bereitstellung von kostenlosen Zusatzdiensten in diesem Zeitraum (z.B. Ladekarte für öffentliche Ladesäulen, persönlicher Betreuer bei technischen Fragen über „Notruffunktion" im Fahrzeug).

6.3.5 Unterstützung der Reichweiteninteraktion im Alltag

Bei der Unterstützung der Reichweiteninteraktion im Alltag geht es besonders darum, die Nutzerfreundlichkeit hinsichtlich der Reichweite zu erhöhen, also im Alltag eine möglichst große nutzbare Reichweite und ein optimales Nutzererleben zu gewährleisten. Es ist daher wichtiger, Nutzern eine verlässlich nutzbare Reichweite zu bieten anstatt eine möglichst hohe technische (maximal mögliche) Reichweite anzustreben. Denn am Ende zählt für das Reichweitenerleben nicht die technische Reichweite, sondern die im Alltag tatsächlich (mit einem guten Gefühl) nutzbare Reichweite. Eine große Differenz zwischen technischer und subjektiv nutzbarer Reichweite kann hier zur Enttäuschung von Nutzererwartungen führen (siehe auch Artikel 1, Abschnitt 3.1). Im Sinne der Reduzierung möglicher Diskrepanzen zwischen den verschiedenen Reichweitenschwellen (siehe 4.1.1) ist es daher essentiell (1) real erreichbare Reichweiten zu kommunizieren (technische Reichweite), (2) die Nutzer zu befähigen, bei Bedarf eine möglichst hohe Reichweite erreichen zu können (kompetente Reichweite) und (3) die Unsicherheiten bezüglich der verfügbaren (angezeigten) Reichweite möglichst zu reduzieren, damit Nutzer mit einem guten Gefühl (komfortable Reichweite) die verfügbare Reichweite (performante Reichweite) vollständig ausnutzen (Unsicherheit scheint ein zentraler Faktor für die suboptimale Reichweitenausnutzung zu sein, siehe Artikel 1, Abschnitt 3.1).

Wie kann man Nutzern also die Interaktion mit der Reichweite erleichtern und damit eine nachhaltige Interaktion mit dem Elektromobilitätssystem (z.B. bessere Fahrtentscheidungen) fördern? Entscheidend für die Reduzierung der Diskrepanz zwischen komfortabler und performanter Reichweite ist der Berechnungsalgorithmus für die Reichweite. Dieser muss möglichst genau und gleichzeitig nachvollziehbar sein. Je mehr Faktoren der Algorithmus für die Vorhersage der Reichweite einbezieht (vergleichbar mit einem hohen Automatisierungsgrad eines Assistenzsystems), desto geringer fällt potentiell die Unsicherheit beim Nutzer und damit unter Umständen auch der Reichweitensicherheitspuffer aus. Damit Nutzer der Berechnung vertrauen und gleichzeitig auch auf Systemgrenzen reagieren können, ist hier jedoch auch die Transparenz (Nachvollziehbarkeit) der einbezogenen Faktoren entscheidend (siehe auch Artikel 1, Abschnitt 3.1). Es geht hier also darum, wie man den Fahrer in der Kontrollschleife („in the loop") hält (Merat & Lee, 2012). Durch einen hohen Automatisierungsgrad der Reichweitenvorhersage kann es zu einem Kompetenzverlust kommen (Bainbridge, 1983). Die Nutzer sind so gegebenenfalls nicht mehr fähig, die Wirkung von Faktoren, die nicht vom Reichweitenalgorithmus einbezogen werden können (z.B. Änderung der Verkehrssituation/Strecke), einzuschätzen, beziehungsweise achten die Nutzer weniger auf solche Einflussfaktoren und verlassen sich allein auf die Reichweitenvorhersage des Systems (Problem der over-reliance, siehe z.B. Popken & Krems, 2011).

Darüber hinaus weisen die Subjektivität des Reichweitenerlebens und der Zusammenhang von *subjektiver* Kompetenz und komfortabler Reichweite (siehe Artikel 1, Abschnitt 3.3; Artikel 2, Abschnitt 3.3) darauf hin, dass es für die Reduzierung der Diskrepanz zwischen komfortabler und performanter Reichweite letztendlich darum geht, die *subjektive* Kontrollierbarkeit und Vorhersagbarkeit der Reichweitensituation zu steigern. Es ist also wichtig, einfach erreichbare Handlungsmöglichkeiten für die Nutzer zu schaffen (z.B. Änderung des Fahrmodus, Suche nach Lademöglichkeiten), welche die Reichweite verlängern, als Sicherheitsoptionen dienen, oder ganz allgemein die Anspannung (den antizipierten Stress) abbauen können.

Entscheidend für eine hohe kompetente Reichweite ist das Anzeigesystem für den Reichweitenverbrauch. Dieses muss die Effekte von Nutzereingriffen genau, verständlich und zeitlich adäquat aufgelöst abbilden, damit es für die Nutzer möglich wird, die Reichweitendynamik zu explorieren, die Möglichkeiten zur Beeinflussung der Reichweite zu verstehen, und letztendlich eine präzise und zeitlich hochaufgelöste Kontrolle des Reichweitenverbrauchs ausüben zu können. Ideal scheint hier eine direkte Anzeige des Verbrauchs in erzielbarer Reichweite (welche Reichweite wäre basierend auf Energieverbauch der z.B. letzten 5 Minuten möglich), damit Nutzer nicht zwischen verschiedenen Kenngrößen (aktuell meist Reichweitenvorhersage basierend auf den letzten 30-50 km versus Verbrauchshistorie mit kurzem Aggregationsintervall in kWh) umrechnen müssen, sondern vielmehr eine direkt mit den Mobilitätsressourcen verknüpfte Einheit zur Verfügung haben.

Damit solche Strategien jedoch tatsächlich zu einer besseren (nachhaltigeren) Reichweitenausnutzung beitragen, sollten mögliche Effekte negativer Verhaltensanpassung berücksichtigt werden (siehe z.B. Breyer, Blaschke, Färber, Freyer, & Limbacher, 2010; Young, Regan, Triggs, Jontof-Hutter, & Newstead, 2010). Denn eine hohe komfortable Reichweite (ein geringer Reichweitensicherheitspuffer) könnte beispielsweise zu einem geringeren Erwerb von Strategien zur Reichweitenverlängerung (geringere kompetente Reichweite) und zu einer Aneignung eines weniger sparsamen Fahrstils (geringere performante Reichweite) führen (siehe auch Diskussion dazu in Artikel 1, Abschnitt 4.1; Artikel 2, Abschnitt 4, vierter Absatz).

Schließlich geben die Ergebnisse dieser Arbeit auch Hinweise auf die Sinnhaftigkeit versteckter Reichweitenreserven. Einige aktuelle Elektrofahrzeuge haben eine verstecke Reichweitenreserve, fahren also auch noch nach der Anzeige von 0 km Restreichweite weiter. Ein Teil der Batterieressourcen wird also als technischer Sicherheitspuffer eingesetzt und steht dem Fahrer so als im Alltag nutzbare Reichweite nicht direkt zur Verfügung. Basierend darauf, dass die Nutzer bei ihren Fahrtentscheidungen selbst einen substantiellen Sicherheitspuffer einplanen (siehe Artikel 1 und 2) und das Fahrzeug in der Regel noch mit erheblichen Restressourcen wieder aufladen (siehe Artikel 3), scheint es eher nicht sinnvoll eine versteckte Reichweitenreserve zu integrieren.

6.4 Kritische Reflexion der Studienmethodik

Bei der Interpretation der Befunde in dieser Dissertation sind einige kritische Aspekte zu beachten. Diese betrifft insbesondere Eigenheiten der Stichprobe sowie Eigenheiten der Feldstudienmethodik.

6.4.1 Eigenheiten der Stichprobe

Die Rekrutierung der Teilnehmer für die Feldstudie „MINI E Berlin powered by Vattenfall“ wurde über eine öffentlich beworbene Bewerbungsplattform realisiert. Die Nutzer mussten für das Fahrzeug eine monatliche Nutzungsrate von 400 Euro bezahlen und die Möglichkeit haben, eine Ladestation zu installieren. Durch den spezifischen Selektionsprozess kann angenommen werden, dass die Stichprobe Early Adopter (Rogers, 2003) von Elektrofahrzeugen in urbanen Regionen abbildet. Diese weichen im soziodemographischen Profil (siehe Vergleich in Artikel 4, Abschnitt 3.2) nicht aber im Mobilitätsprofil (siehe Abschnitt 6.3.1) vom typischen deutschen Autofahrer ab. Early Adopter akzeptieren (bzw. überwinden) Nutzungsbarrieren eher als der Durchschnittsnutzer (siehe z.B. Barjak et al. 2009). Auch in dieser Studie schienen die Nutzer sehr motiviert, den Umgang mit der Reichweite zu erlernen. Zusätzlich hatten die meisten Fahrer während der Studie guten Zugang zu einem Alternativfahrzeug. Es kann also davon ausgegangen werden, dass die Befunde tendenziell eher die Obergrenze der Nutzerzufriedenheit und der Reichweitenausnutzung (komfortable, performante, kompetente Reichweite), beziehungsweise die Untergrenze der Reichweitenpräferenzen und des Reichweitenstresses unter den gegebenen Mobilitätsbedürfnissen und -mustern darstellen. Die 75-80% Reichweitenausnutzung stellen also beispielsweise vermutlich einen eher optimalen Wert dar. Allerdings werden in den nächsten Jahren wahrscheinlich die typischen Early Adopter auch zunächst einen Großteil der Käufer von Elektrofahrzeugen ausmachen.

Die Implikationen der Spezifität der Stichprobe für die untersuchten Zusammenhänge sind geringer. Es ist zumindest nicht anzunehmen, dass diese Effekte in anderen Nutzergruppen grundlegend anders geartet sind. Allerdings ist bekannt, dass Early Adopter eher bestimmte Persönlichkeitseigenschaften aufzeigen (Rogers, 2003), was sich beispielsweise auch in den Artikeln 1 und 2 in einer Varianzbeschränkung bei bestimmten Persönlichkeitsmerkmalen (z.B. überwiegend hohe bis sehr hohe internale Kontrollüberzeugungen) andeutet. Dies könnte zu einer ungenaueren Schätzung einiger Zusammenhänge geführt haben.

6.4.2 Eigenheiten der Feldstudienmethodik

Durch die Vielfalt an Forschungsthemen der Feldstudie mussten die Konzepte mit vergleichsweise kurzen Skalen erfasst werden, was ein Problem für die Reliabilität darstellen kann. Eine formale Skalenentwicklung inklusive Vortestung mit Itemselektion war ebenfalls nicht möglich, da fast alle Fragen nur von erfahrenen Elektrofahrzeugnutzern sinnvoll beurteilt werden konnten und diese erst im Rahmen der Feldstudie zur Verfügung standen. Insgesamt könnten einige Regressionsergebnisse dadurch beeinflusst sein (Stade, Meyer, Niestroj, & Nachtwei, 2011).

Das Ziel des Studiendesigns war eine hohe ökologische Validität. Durch die Eigenheiten des Feldstudiendesigns ließen sich jedoch viele Faktoren nicht kontrollieren (z.B. Vorwissen und erhaltene Informationen während der Nutzung). Auch wurde nur eine spezifische Konfiguration eines Elektromobilitätssystems getestet. Dabei war insbesondere das Fahrzeug (der MINI E) sehr spezifisch (z.B. sehr positives Fahrzeugimage durch Marke MINI, Zweisitzer mit minimalem Kofferraum). Bei einem anderen Fahrzeug wären einige Beurteilungen möglicherweise anders ausgefallen. Für das Erleben und Verhalten im Umgang mit der Reichweite sollten diese Spezifika des MINI E jedoch einen eher geringen Störeinfluss darstellen. Die alleinige Testung eines Elektromobilitätssystems hatte aber auch Vorteile, da die geringere Variation bei den Eigenschaften des technischen Systems es leichter machte, interindividuelle Unterschiede zu untersuchen. Da der MINI E nur einen Fahrmodus und nur grundlegende Informationen zu Reichweite und Verbrauch bereitstellte, waren auch die Freiheitsgrade bei der Interaktion mit der Reichweite etwas geringer, was ein Vorteil für die Untersuchung bestimmter Fragestellungen des Reichweitenerlebens darstellte. Schließlich waren auch durch die täglich verfügbare private Lademöglichkeit die Ladebedingungen in einem gewissen Rahmen standardisiert, was günstig für die Untersuchung der interindividuellen Unterschiede im Ladeverhalten war.

Durch das korrelative Forschungsdesign sind viele Ergebnisse nicht kausal interpretierbar, die Richtung von Effekten kann also teilweise nur indirekt aus der angenommenen unterschiedlichen Stabilität bestimmter Variablen gemutmaßt werden. Damit ergibt sich beispielsweise aus dem Effekt des Vorwissens zu Studienbeginn auf die kompetente Reichweite nach 3 Monaten praktischer Erfahrung nicht zwangsweise, dass die Vermittlung von mehr Vorwissen auch zu einer besseren kompetenten Reichweite führt. Hohes Vorwissen könnte sich theoretisch auch aus einer Variable als Nebeneffekt ergeben und eben diese Variable (z.B. generelles Interesse für technische Zusammenhänge) ist schließlich der eigentliche Wirkfaktor für eine hohe kompetente Reichweite.

Schließlich erlaubte die Stichprobengröße teilweise nicht, das eigentlich optimale Analyseverfahren zu rechnen (z.B. multiple Regression mit mehr als zwei Prädiktoren).

6.5 Ertrag für die psychologische Forschung

Die zunehmende Elektrifizierung des Individualverkehrs stellt sich inzwischen als voraussichtlich stabile Entwicklung dar (Gaide, 2009; Hajesch, 2013; Kohler, 2010). Der Umgang mit der elektrischen Reichweite zeigt sich hier bei allen Fahrzeugkonfigurationen als ein zentrales Thema der Nutzerforschung (siehe z.B. auch Ausführungen in Abschnitt 2.2). Die Nutzerinteraktion mit der Reichweite wird die Verkehrspsychologie der nachhaltigen Mobilität und die Ergonomie daher wahrscheinlich noch länger beschäftigen. Damit stellen die eingeführten psychologischen Konzepte, das Prozessmodell, die entwickelten Skalen und methodischen Ansätze, die untersuchten Einflussfaktoren, und schließlich die Befunde aus dieser Dissertation möglicherweise eine fruchtbare Grundlage für die weitere Forschung dar.

Prozesse der Verhaltensanpassung bei der Nutzung neuer technischer Systeme (insbesondere Assistenzsysteme) sind ein aktuelles Thema (Rudin-Brown & Jamson, 2013; Stevens, Krems, & Brusque, 2014) in der Verkehrspsychologie. Auch die vorliegende Dissertation hat sich mit Verhaltensanpassung beschäftigt (siehe z.B. auch die Einordnung von Artikel 2 im Leitartikel zum Special Issue von Gehlert et al., 2013) und verschiedene Einflussfaktoren auf den interindividuell unterschiedlichen Erfolg der Anpassung identifiziert. Auch das Modell der adaptiven Kontrolle von Reichweitenressourcen beschäftigt sich zentral mit Anpassungsprozessen. Hierfür spricht auch, dass die zwei verwandten kontrolltheoretischen Modelle von Fuller (2005) und Summala (2007) im Buch von Rudin-Brown und Jamson (2013) als aktuelle Modelle für Verhaltensanpassung angeführt werden (Lewis-Evans et al., 2013). Es scheint also durchaus möglich, dass diese Dissertation auch eine Bereicherung für das Feld der Verkehrspsychologie der Verhaltensanpassung darstellt.

Wie in Abschnitt 2.1 dargelegt, befindet sich auch das Themenfeld der Mensch-Technik-Interaktion im Bereich der nachhaltigen Mobilität in einer Zeit der starken Entwicklung und der Forschungsstand zu Ergonomie und Nachhaltigkeit ist noch relativ begrenzt (Haslam & Waterson, 2013). Die vorliegende Arbeit konnte zeigen, dass viele Aspekte von Modellen aus dem Bereich der Verkehrssicherheit (sicheres Fahrverhalten) auch auf das Feld der nachhaltigen Mobilität übertragbar sind (z.B. Konzept der Sicherheitsgrenze, Konzept des Fahrstils). Darüber hinaus konnte auch gezeigt werden, dass es bei der Entwicklung von Konzepten in diesem Bereich hilfreich sein kann, mögliche Analogien zu anderen Mensch-Technik-Systemen stärker zu explorieren, da beispielsweise auf dem Gebiet der Mensch-Computer-Interaktion schon etwas länger der Umgang mit batteriebetriebenen mobilen Geräten (Rahmati & Zhong, 2009) und das Thema umweltbezogene Nachhaltigkeit (Blevis,

2007) erforscht werden. Schließlich scheint das in dieser Arbeit entwickelte Modell unter Umständen auch auf ähnliche Ressourcenkonflikte in Mensch-Technik-Systemen und verwandte Fragestellungen der nachhaltigen Mobilität übertragbar zu sein (siehe Abschnitt 6.2.6).

Im Sinne eines methodischen Beitrags wurde in dieser Dissertation aufgezeigt, dass ein Multimethodenansatz, bei dem verschiedenste Datenquellen verknüpft werden (qualitative Daten, Fragebögen, Tagebuchverfahren, Datenlogger), dabei helfen kann, in Feldstudiensettings zu einem umfassenden und differenzierten Verständnis des Nutzererlebens und -verhaltens zu gelangen. Auch wurde gezeigt, dass die Beschäftigung mit individuellen Unterschieden und den Einflussfaktoren auf diese Unterschiede ein fruchtbarer Ansatz sein kann, um in einem Feldstudiensetting ein Verständnis des Nutzererlebens und -verhaltens zu erlangen. Gerade in einem neuartigen Mensch-Technik-System scheint dies ein fruchtbarer Ansatz und Startpunkt für eine Optimierung der Nutzerfreundlichkeit. Mit einer in den nächsten Jahren zu erwartenden Zunahme der Vielfältigkeit von neuartigen nachhaltigen Antriebskonzepten wird sich diese Forschungssituation eventuell wiederholen. In solchen Fällen kann die methodische Herangehensweise dieser Arbeit möglicherweise hilfreiche Anregungen bieten.

Schließlich besteht eine Möglichkeit, den Beitrag der vorliegenden Dissertation zur Forschung im Bereich der nachhaltigen Mobilität zu beurteilen darin, die Einordnung der Artikel in der nachfolgenden Literatur zu betrachten. Beispielsweise stellen Dimitropoulos et al. (2013) im Rahmen einer Metaanalyse zu Reichweitenpräferenzen heraus, dass Artikel 2 und Artikel 1 darauf hinweisen, dass das Reichweitenerleben dynamisch ist und dass durch (unterstütze) Anpassungsprozesse geringere Reichweiten eher als zufriedenstellend wahrgenommen werden können und dies dementsprechend bei der Forschung zu Reichweitenpräferenzen berücksichtigt werden muss. Des Weiteren schlussfolgern Neaimeh, Hill, Hübner, und Blythe (2013) basierend auf den Ergebnissen zu den Reichweitenschwellen aus Artikel 2, dass es aufgrund der identifizierten substantiellen Reichweitensicherheitspuffer und der scheinbaren Veränderbarkeit der Reichweitenschwellen wichtig ist, Fahrern eine hohes Vertrauen in ihre verfügbare Reichweite zu geben. Die Autoren nehmen dies als Ausgangspunkt für ihre Untersuchungen zur Steigerung der Genauigkeit der Reichweitenvorhersage bei Elektrofahrzeugen. Die Schlussfolgerung aus Artikel 1 und 2, dass die Ergebnisse darauf hindeuten, dass Algorithmen zur Reichweitenvorhersage verbessert werden müssen, wird auch von anderen Forschergruppen aufgegriffen (z.B. Rodgers & Zoepf, 2013, Verweis auf Artikel 1). Darüber hinaus betont Matthies (2013) in ihrem psychologischen Literaturüberblick zum Nutzerverhalten in Energiesystemen, dass insbesondere die Ergebnisse zu den in Artikel 2 untersuchten psychologischen Einflussfaktoren auf das Reichweitenerleben eventuell eine fruchtbare Grundlage für weitere Forschung zur Nutzerperspektive auf Elektromobilität darstellen könnten. Des

Weiteren wird in der Literatur die Implikation aus Artikel 1 wiederholt aufgegriffen, dass das Befundmuster dafür spricht, dass psychologisch fundierte Interventionen und ein entsprechendes Design von Nutzerschnittstellen eine Möglichkeit bieten, um die psychologische Reichweitenbarriere zu überwinden (Dudenhöffer, 2013; Hjorthol, 2013; McIlroy et al., 2013). Besonders umfassend geht hierbei der aus der Perspektive der Ergonomie verfasste Literaturüberblick von McIlroy et al. (2013) auf die verschiedenen Designimplikationen aus Artikel 1 ein.

Insgesamt kann also geschlussfolgert werden, dass die vorliegende Dissertation einen gewissen Beitrag zur Forschung im Bereich nachhaltiger Mobilität leisten konnte und dass die Befunde unter Umständen auch über dieses Themenfeld hinaus, zum Beispiel für das Verständnis der Interaktion mit knappen Ressourcen in anderen Mensch-Technik-Systemen oder allgemein im Zusammenhang mit dem Verständnis von Anpassungsprozessen nützlich sein könnten.

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II Artikel 1: Experiencing range in an electric vehicle: Understanding psychological barriers

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Experiencing Range in an Electric Vehicle: Understanding Psychological Barriers

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Range of electric vehicles (EVs) has long been considered a major barrier in acceptance of electric mobility. We examined the nature of how range is experienced in an EV and whether variables from other adaptation contexts, notably stress, have explanatory power for inter-individual differences in what we term comfortable range. Forty EVs were leased to a sample of users for a 6-month field study. Qualitative and quantitative analyses of range experiences were performed, including regression analyses to examine the role of stress-buffering personality traits and coping skills in comfortable range. Users appraised range as a resource to which they could successfully adapt and that satisfied most of their daily mobility needs. However, indicators were found that suggested suboptimal range utilisation. Stress-buffering personality traits (control beliefs, ambiguity tolerance) and coping skills (subjective range competence, daily range practice) were found to play a substantial role in comfortable range. Hence, it may be possible to overcome perceived range barriers with the assistance of psychological interventions such as information, training, and interface design. Providing drivers with a reliable usable range may be more important than enhancing maximal range in an electric mobility system.

1 INTRODUCTION

How far does it go? Most often, this is one of the first questions that come into people's minds when hearing of a new electric vehicle. For most novices in the field, the perception of limited mobility resources is a barrier to purchasing intentions (e.g. Bunch, Bradley, Golob, Kitamura, & Occhiuzzo, 1993; Thomas, 2010). Also, from an expert point of view, EV batteries, which essentially represent range, are often evaluated as most problematic for the

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success of electric mobility systems (e.g. Kitamura & Hagiwara, 2010). However, relying on existing range data drawn from travel surveys (Duke, Andrews, & Anderson, 2009; Greene, 1985) and feedback from expert EV users (Gärling, 2001; Krems, Franke, Neumann, & Cocron, 2010), EVs should easily be able to meet most travel needs. Hence, is the experience of range as barrier mainly a psychological issue?

Although EV field trials have a long-standing tradition (e.g. Bish & Tietmeyer, 1983; Patil, 1990), there is very little published research about the nature of how real users experience EV range and how they subsequently deal with it. Many field trials have focused on assessing technical variables (Francfort, Bassett, Briasco, Culliton, Duffy, Emmert, Hague, Hobbs, Graziano, Kakwan, Neal, Stefanakos, & Ware, 1998; Goldstein, Koretz, & Harats, 1996), and few have examined overt user behavior or general user satisfaction with EVs (Eden, Heber, Höpfner, & Voy, 1997; Francfort & Carroll, 2001). Psychological processes underlying user experience have thus far only been covered by studies with inexperienced potential users (Chéron & Zins, 1997; Kurani, Turrentine, & Sperling, 1996). In such novices, personal safety buffers have been studied as relevant variables for an anticipated interaction with range, and have been shown to increase perceived range needs (Kurani, Turrentine, & Sperling, 1994). Moreover, there is some evidence that EV users tend to underutilise given range resources (Botsford & Szczepanek, 2009; Golob & Gould, 1998). The phenomenon of range anxiety, which has been heavily discussed in the literature and public media (e.g. Rahim, 2010; Tate, Harpster, & Savagian, 2009), might contribute to this effect but only anecdotal evidence has been reported on this topic, for example, by research with EV1 users (Tate et al., 2009). In sum, scientific knowledge of range experience in real users is scarce

The objective of the present research was to achieve a better understanding of range experience in experienced EV drivers. This was done by applying a field trial approach with 40 EVs leased to customers from the general public for a 6-month period. On the basis of the existing literature we formulated the concept of comfortable range and related it to theories of stress and self-regulation. To meet the research objective we examined (1) the prominent conceptual dimensions of range experience, (2) quantitative indicators of range experience in terms of range satisfaction and concerns, as well as comfortable range, and (3) the role of stress-buffering personality traits and coping skills in comfortable range. The practical aim of this research is to provide alternative ways of dealing with the generally perceived barrier imposed by the experience of range, aside from exclusively improving battery performance. With knowledge of how users experience and interact with range, user training and design of the human machine interface (HMI) could be improved.

1.1 Psychological Range Levels in an EV

To characterise the nature of range experience and range utilisation, reports have focused on concepts such as anxiety or fear (e.g. Botsford & Szczepanek, 2009). However, further factors might play a role. Psychological theory suggests that physically identical situations may constitute a fundamentally different psychological situation for different individuals (Bowers, 1973; Lazarus & Folkman, 1984). In the domain of range, we propose four levels that influence the transition from the objective physical situation to the subjective psychological situation. First, *cycle range* is measured according to a standardised driving schedule (e.g. Urban Dynamometer Driving Schedule; Kruse & Huls, 1973). It acts as an objective point of reference for the three following psychological range levels that are characterised by different basic psychological correlates. Second, *competent range* is analogous to the concept of linguistic competence (Chomsky, 1965). This is the range that each individual user could obtain based on his eco-driving competence and system knowledge. In EVs, energy consumption is influenced, in particular, by use characteristics (Romm & Frank, 2006) with differing and possibly more complex dynamics than those in internal combustion engine (ICE) vehicles. Operators have been found to experience difficulties in such complex problem solving or control task situations (Frensch & Funke, 1995). Thus it is likely that there will be a gap between the competent range of individual users and the cycle range of the EV. Third, *performant range* is analogous to the concept of linguistic performance (Chomsky, 1965), usually obtained by each user based on his eco-driving-related motivational strengths and habits. Driving behavior is influenced by various motives (Gregersen & Berg, 1994; Steg, 2005) with range optimisation being only one among others and, hence, performant range will likely be lower than competent range.

Most important for range experience, *comfortable range* refers to the range that users really utilise. This can be defined as the highest trip distance between two charging opportunities or the lowest remaining range status which a user experiences as comfortable. This definition attempts to merge absolute value range buffer decision variables (Kurani et al., 1994) with the broadly defined concept of range anxiety in terms of a "fear of becoming stranded" (Tate et al., 2009, p. 158). Comfortable range may reflect the result of an adaptation process that involves anchors and heuristics from internal combustion engine (ICE) powered mobility systems, and ultimately result in an equation involving individually perceived levels of performant and competent range. Furthermore, personal dispositions for coping with uncertainty or risk may be included in this equation. In summary, comfortable range reflects the perceived balance between mobility needs (e.g. journey distance, route profile, trip purpose) and mobility resources (e.g. remaining range, individual coping skills) for a certain journey. The great number of influencing factors implies a high potential variation in comfortable range. A better understanding of these dynamics could help to develop measures against perceived EV range barriers.

1.2 A Conceptual Framework for Understanding Comfortable Range

As described above, having a low remaining range for a certain journey can be conceived as having low mobility resources to reach personal goals or to meet external demands set by the environment (mobility needs). Imagine an EV user whose goal is to have a comfortable and timely commute to work, when a traffic jam requires the driver to take a longer route and energy resources are already partially depleted. Here, the notion of a critical person–environment imbalance bears similarities with common definitions of stress (Lazarus & Folkman, 1984). Among the most influential concepts of stress, the transaction model (Lazarus & Folkman, 1984) states that stress is the result of a perceived imbalance between the demands existing within a person's environment and available resources that the person possesses. In a continuous circular appraisal process, relevant demands from the environment are evaluated as either challenge versus threat versus harm/loss, and further appraised in terms of subjective capabilities to cope with stress-inducing factors.

As in the previous discussion of comfortable range, this model points to the inherently subjective nature of the perceived stressfulness of a given situation. It implies that reducing stressors (e.g. simply increasing range) is only one way to cope with the stressful situation. Another solution lies in influencing an individual's appraisal process, which in turn can lead to higher stress resistance. Personality characteristics, effective coping strategies, and social support can lead to a lower level of experienced stress (Holahan & Moos, 1990). Hence, personal resources are vital for stress resistance. A wide range of stress-buffering personality traits have been discussed (Connor-Smith & Flachsbart, 2007; Contrada & Baum, 2009). Internal control beliefs have been evaluated as a central variable. It has been addressed extensively in the original work of Lazarus and Folkman (1984) and also in the driving domain (Gulian, Matthews, Glendon, Davies, & Bedney, 1989; Holland, Geraghty, & Shah, 2010). Tolerance of ambiguity is another variable that has been linked to stress resistance in the original work of Lazarus and Folkman (1984) and also in more recent contributions (Frone, 1990; Furnham & Ribchester, 1995; Greco & Roger, 2003). Because of the complex dynamics of range, which result in particularly ambiguous situations for users, this personality trait variable may play an especially relevant role in range stress. Regarding the second set of protective factors, effective coping strategies, highly developed knowledge and skills to deal with certain situations, and high levels of practice with certain technical systems can lead to a reduction in experienced stress (Holland et al., 2010; Lazarus & Folkman, 1984).

Yet, do EV users really experience range stress? There is some indication that comfortable range is strongly influenced by anticipation of stressful situations, but that the experience of range stress or range worries is uncommon in EV drivers. One reason for this could be that users have ways to reduce stressors, including available ICE vehicles or other means of transportation at hand that could facilitate avoiding stressful remaining-range situations. Thus, the avoidance of stress might characterise range experience more than the experience of stress itself. However, the theoretical framework of stress also has explanatory power for more general forms of adaptation processes. The transactional stress model, as with many other stress-related theories, has a general control system conception as its structural basis (Leventhal, Halm, Horowitz, Leventhal, & Ozakinci, 2004). This cybernetic approach (Miller, Galanter, & Pribram, 1960) can be fruitfully applied to many areas of adaption and self-regulation (Carver & Scheier, 1998). Following this notion and integrating the above-mentioned references, a general action–control approach may be formulated. In this approach, strong weight is placed on the subjective and affective components of control processes and includes assumptions concerning various personal factors to create a viable foundation for a conceptual framework of comfortable range (Figure 1). While the conceptual framework of comfortable range excludes certain elements of Lazarus' model, it preserves both structure and moderating assumptions, which are also central to many other self-regulation approaches. In the present research, the influence of the reference signal on the comparator is a central component (Figure 1).

To sum up, we have pointed out that range experience in experienced EV drivers is an important topic but is poorly understood. Given that range experience has not yet been systematically assessed, it would seem that a qualitative approach is indicated as a basis from which to begin. Hence, our first research question is: What are the prominent conceptual dimensions of range experience in experienced users? Relevant candidate variables of range experience could be identified from previous research, but have only rarely been assessed comprehensively in experienced drivers. Thus, our second research question is: How do experienced users experience range in terms of satisfaction, range concerns and comfortable range? Finally we have tried to work out a possible connection between models of stress or self-regulation and comfortable range, which lead to the assumption of a relation between stress-buffering personal resources and comfortable range. In view of this potential connection, our third research question

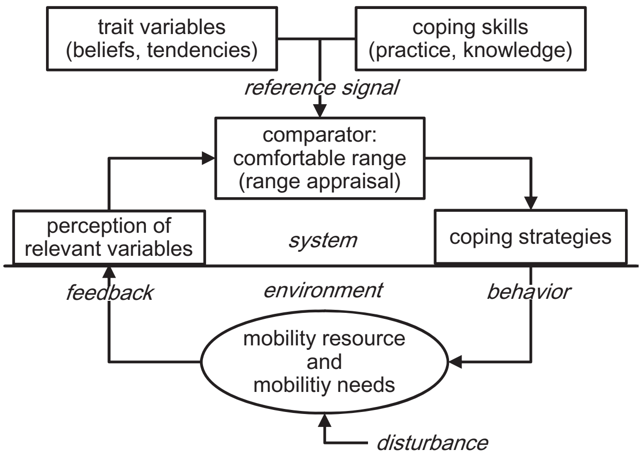

FIGURE 1. Conceptual framework for comfortable range. At the micro-level of range adaptation, mobility resources, such as remaining range and recharging opportunities ahead, are plotted against mobility needs to produce a perceptual signal. This signal is then compared to reference signal variables (e.g. experience with similar situations and general control beliefs) to yield an individual comfortable range (range appraisal) for the current situation. Adaptation strategies are then chosen (e.g. eco-driving) and translated into behavior that again changes the range situation. Substantial environment-based distortion, e.g. influences on consumption, adds noise to this action regulation loop.

is: What is the role of stress-buffering personality traits and coping skills in comfortable range? We hypothesise that stress-buffering personality traits, namely high internal control beliefs and high ambiguity tolerance, are positively associated with comfortable range. Moreover, we assume that high subjective coping skills, namely subjective range competence and daily range practice, reduce range stress and thus increase comfortable range.

2 METHOD

2.1 Field Study Setup

The present research was part of a large-scale EV field trial in the Berlin metropolitan area in Germany. This trial was set up by the BMW Group and Vattenfall Europe and was funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. Within this trial there were two subsequent 6-month user studies with 40 private EV users in each study. The present contribution incorporates data from the 40 users within the first phase. For each user, data were assessed at three time points: prior to receiving the EV (T0), after 3 months of driving (T1), and upon returning the EV after 6 months (T2). For each time point, users filled out a travel diary (all trips occurring within a 1-week period) in advance and then had a 2 h to 3 h face-to-face appointment with one member of the research group in a quiet room at the EV service-hub, where they answered several structured interview questions and filled out questionnaires. These instruments covered several topics, such as mobility, acceptance, charging, range issues, and personal variables with the aim of gaining a comprehensive picture of the customer perspective on EVs in terms of expectations, preferences, experiences, and user behavior. All range experience and coping-skill variables were assessed for experienced drivers (T1, T2), including instructions to refer answers to certain time periods of the study if necessary as T2 was administered following colder weather conditions than T1, and these conditions influenced the range of the EV. Further details on the field trial methodology have been reported elsewhere (Cocron, Bühler, Neumann, Franke, Krems, Schwalm, & Keinath, 2011; Franke, Bühler, Cocron, Neumann, & Krems, 2011; Krems et al., 2010).

2.2 Participants

Participants were recruited via an online screening application that was publicised via advertisements in newsprint and online media. Forty participants for the first usage phase were selected from more than 700 applicants. Conditions of participation included, for example, willingness to pay a monthly lease, and opportunity to install a private charging infrastructure. Further distribution criteria aimed to prevent restriction of variance on basic sociodemographic (age, gender, education) and mobility-related (mileage, vehicle fleet) variables. From each household only the (prospective) main-user of the EV was included in data collection. As restrictions for inclusion in the sample were similar to those for leasing an EV (e.g. users paid a monthly leasing-rate, needed charging opportunity), we expected the sample to represent a population of early EV buyers in German urban areas. The mean age of the 40 selected users was 48 years ($SD = 8.92$), 33 of whom were male, 78 per cent had a university degree, and 25 per cent had completed a doctoral degree. The majority (78%) of user households consisted of two people > 18 years of age (43% had children). In 58 per cent of households, more than one car existed prior to the field trial ($M = 1.88$ cars), whereas only two households had no car. Two users did not complete the study.

2.3 Electric Mobility System

The EV used in this study was a converted MINI Cooper with a cycle range of 250 km. Range information in this vehicle is provided by a state-of-charge display and a remaining range (km) display, which calculates remaining range based on state of charge and energy consumption over the last 30 km. The electric mobility system used herein is further characterised by a regional focus on the urban area of Berlin, including a network of 50 public charging stations in addition to the private charging stations of each user (full charge duration = 4 hr). Although most trips that took place occurred in the metropolitan area of Berlin and its direct periphery, some individual users travelled more than 200 km out of the city.

2.4 Measures of General Range Experience

To examine qualitative dimensions of range experience, the T1 interview asked users, "How have you experienced the range of the EV?" Users' verbally reported answers were recorded and transcribed verbatim for coding in the qualitative data analysis software package MAXQDA. Analysis techniques motivated by grounded theory methodology in the tradition of Strauss and Corbin (1990) were used to gain a deeper understanding of the phenomena surrounding range experience. Open coding of text passages was done line-by-line with conceptual codes. Memos were written at several steps of the coding process and codes were iteratively refined and condensed within axial and selective coding to arrive at an acceptable level of abstraction. Accordingly, a condensed structure of the conceptual dimensions and their relations within users' expressions emerged.

To assess range satisfaction, the questionnaire item, "The range was sufficient for everyday use", was administered at T1. Users indicated their agreement on a 6-point Likert scale ranging from 1 (*completely disagree*) to 6 (*completely agree*). Throughout the study, this was the standard scale for all self-constructed agreement ratings. Users also indicated the percentage of trips that could have been made with the EV if limitations of passenger and cargo space (the EV was a two-seater with a very small trunk) were remediated. This hypothetically eliminated the second big barrier to usage—in comparison to ICE vehicles—which will also be removed in most next-generation EVs.

To determine whether users experienced worries or concerns similar to reported range anxiety in electric mobility systems, two items were administered at T1: "While driving, I was often worried about the range" and "I am more worried about the range in an EV than in a conventional combustion engine vehicle". In addition, two items were included at T2 to give an indication of the frequency with which users experienced stressful range situations over the whole trial. Specifically, users were asked to report how often per month they experienced "being nervous" and "feeling stressed" due to range.

2.5 Measures of Range Appraisal and Comfortable Range

2.5.1 Range Game. The aim of the range game was to precisely assess the individual comfort zone in a standardised, yet ecological valid way. The name of the range game reflects the assumed similarity between uncertainty factors in range and uncertainty in gambles in decision-making research (Hastie & Dawes, 2009). In order to detect a certain threshold, certain aspects of psychophysical methodology (Gescheider, 1997) were adopted. As instruction, participants were shown a map of Berlin, which was marked with a 60-km route through the city. They were told that there were no charging opportunities along this route. Afterwards, they received 10 four-item questionnaire cards in random order, including the same four items but with differing information about the remaining range at the beginning of the route (from 45 to 90 km). There were two negatively formulated statements ("I am concerned about reaching the destination" and "I wish I had another car to make this trip") and two positively formulated statements ("I am sure I will reach the destination with my EV" and "On this trip, I will not be worried about range"). The remaining range on each card referred to the EV range display, which based its estimation on current battery status and energy consumption over the last 30 km. This aspect induced an ecologically valid level of range uncertainty. Data were checked for extreme outliers as a few participants had problems with a double negative in the last item above. For two people a single value was excluded because it was an extreme outlier in relation to the other three item values of these users. For scoring, the highest remaining distance where users no longer felt perfectly comfortable with the range (i.e. scale value changing from 6 to 5) was selected for each of the four items. These four scores yielded a Cronbach's alpha of .95. A composite mean score was computed from all four item scores. This final score was defined as the operationalisation of a user's individual range comfort zone for the corresponding standard situation provided in the game. The range game was administered at T1.

2.5.2 Range Threat Appraisal. The primary appraisal secondary appraisal (PASA) questionnaire assesses facets of stress appraisal in concrete situations with reference to Lazarus' transactional model (Lazarus & Folkman, 1984). It can be adapted to many stress-inducing situations without changing item wording. It has been used for measuring effects of stress management training (Hammerfald, Eberle, Grau, Kinsperger, Zimmermann, Ehlert, & Gaab, 2006) and for the evaluation of exposure therapy (Gaab, Jucker, Staub, &

Ehlert, 2005). At T2, users in the present study were instructed to imagine a situation where the displayed remaining range of the EV and remaining trip distance were equal. Participants indicated their response to items such as "I do not feel threatened by the situation" on a 6-point Likert scale. The four-item threat-appraisal scale (Cronbach's alpha = .81) was selected for the present analyses as it best represents what should be eliminated to improve range experience (e.g. a high challenge appraisal is far less critical) and also because of its economy in comparison to the alternative 16-item stress-index score with which it was also strongly correlated ($r = .86$).

2.5.3 Maximum Comfortable Trip Distance. To directly assess range resources that users were comfortable with utilising they were requested to indicate a numerical value in km for the questionnaire item: "From which total distance between two recharging opportunities, for fully charging the EV (e.g. wallbox to wallbox) did you, or would you, no longer use the EV if there was no time/opportunity for an intermediate charge?" There was one extreme outlier (30 km) in this variable that was also an extreme outlier in relation to other comfortable range variables of this user, and was therefore excluded from the analyses. The item was administered at T2.

2.5.4 Range Safety Buffer. The safety buffer item assessed the minimum remaining range that users were comfortable with when using the EV. A numerical value in km had to be indicated for a response to the item: "Which range buffer do you set yourself, below which you would not be willing to drive the EV anymore (except in exceptional circumstances)?" The item was administered at T2.

2.6 Measures for Stress-Buffering Personality Traits

2.6.1 Control Beliefs. Control beliefs were assessed with the KUT (control beliefs in dealing with technology; Beier, 1999) containing items such as "Technical devices are often inscrutable and hard to handle". The scale is conceptualised within social learning theory (Rotter, 1966) and is based on the IPC by Levenson (1972). The scale has been used in different fields of technology (Beier, Spiekermann, & Rothensee, 2006). The short form of this scale with eight items (6-point Likert scale) and original instructions was applied (Cronbach's alpha = .90, $M = 5.00$, $SD = 0.74$).

2.6.2 Ambiguity Tolerance. The eight-item ambiguity tolerance scale of Dalbert (1999) was used. This scale builds on the work of Frenkel-Brunswik (1949) and has been used, for example, in pedagogic contexts (König & Dalbert, 2004). Users answered items such as "I only deal with solvable tasks" on a 6-point Likert scale. Cronbach's alpha was .80 ($M = 3.66$, $SD = 0.79$).

2.7 Measures for Stress-Buffering Coping Skills

2.7.1 Subjective Range Competence. The subjective individual skills for coping with (remaining) range of an EV were measured with four items: "I know the energy consumption of my EV", "I know how far I can go on a full charge", "I can precisely estimate the influence of different factors on range", "The range of my EV is mostly affected by factors that I have no influence over". It was assumed that successful coping with range of the EV included feeling confident in predicting remaining range as well as feeling in control of a number of influential factors. The items were administered at both T1 and T2 to gain a picture of range competence under different conditions. The mean score of the four items (last item reversed) yielded Cronbach's alpha values of .75 (T1) and .61 (T2). Similar scale values were obtained for both time points (T1: $M = 4.31$, $SD = 0.74$; T2: $M = 4.16$, $SD = 0.66$), resulting in a strong correlation ($r = .63$). Hence, for the analyses a mean score was computed that included both scale values (T1 and T2).

2.7.2 Daily Range Practice. The objective measure for range skill, as evidenced by daily practice, stems from data obtained in the travel diary where users recorded every trip made with every means of transportation, over a 1-week period. The instrument was constructed in accordance with nationwide travel surveys (Kunert & Follmer, 2005). The diary was a person-based record of all main-user EV trips. Only the data from the T1 travel diary were used because there were too many missing values at T2. Daily range practice was assumed to incorporate two interrelated aspects: Frequency of range considerations before a trip (trip planning, range and distance estimation) and exposure to dealing with range on a trip (experiencing range dynamics, having the chance to improve eco-driving skills). As indicators for these two aspects the mean daily number of trips ($M = 2.91$, $SD = 1.24$) and the mean daily distance driven with the EV ($M = 34.84$ km, $SD = 21.72$) were computed for each user. Only the data from the five weekdays were used as several users reported that weekend trips were atypical and users also had several missing values for weekend days. The two sub-indicators for range practice were strongly correlated ($r = .61$). A mean score was computed from the two z-standardised variables.

3 RESULTS AND DISCUSSION

The main objective of the present research was to achieve a better understanding of individual range experience in experienced EV drivers. In the following, we present the results of the qualitative analysis of the prominent dimensions of range experience, quantitative indicators of range experience, and multiple regression analyses for assessing the role of stress-buffering personality traits and coping skills in comfortable range.

3.1 Range Experience Qualities in an EV

For the interview question, "How have you experienced the range of the EV?", answers from 36 users could be analyzed that provided sufficient information for coding. Four overarching dimensions of range experience emerged from the analysis: (1) rational evaluation of range resource sufficiency (as the core dimension); (2) emotional reaction to experienced range; (3) adaptation processes and strategies with the sub-categories heuristics, safety strategies, approach versus avoidance; and finally (4) uncertainty regarding range dynamics.

The core quality that emerged from this analysis is that range was experienced as a major resource used for interacting with an electric mobility system. That is, users evaluated range centrally in terms of its level of sufficiency. Most users (29 of 36) stated that range was sufficient. Only a few users (7 of 36) were not satisfied with the range. Examining user statements more closely, it was found that most users (28 of 36) spontaneously elaborated on trips that could and could not be made with a given range, which may in turn be generalised as mobility needs that one could or could not fulfill with the range resources provided by the EV. Fit of the EV to normal mobility needs was typically mentioned early in users' transcripts.

Regarding the emotional dimension of range experience, users never mentioned range as a feature that made them feel especially positive about the EV. However, for a few users dissatisfied with range, negative emotional states resulted, and the most prominent of these was annoyance (three of seven users). The absence of positive emotions could also be a Zeitgeist effect because today, the range of an ICE vehicle is a primary anchor from which users evaluate the range. This only leaves EV users the option of evaluating reduced range as either neutral or negative. For some users (11 of 36), framing on losses was further reinforced by the fact that they originally expected to match the cycle range of the EV more accurately, and failure to achieve this typically had a sobering effect.

Experiencing range as a resource included additional perspectives. Users provided detailed explanations of the adaptation processes and strategies in the experience-acquisition period as well as those occurring on a daily basis while interacting with range. Within the reported rules learned and routines performed in dealing with the range, users often settled on certain heuristics (22 of 36) to manage the range resources, such as evaluating range in terms of sets of typical trips (e.g. twice to work and back and once shopping) that could be comfortably done with the EV. A general tendency demonstrated by users was the adoption of safety strategies to avoid encountering trouble with an EV's range (17 of 36). Users reported, for example, that they did not make certain trips although they knew that the required distances still lay within range limitations, or they frequently charged the car or topped-up the battery while on a trip to increase their reserve. Individual users experienced the need to apply such strategies differently. More users (19 of 36) were categorised as regarding range as a challenge or problem-solving task to be solved, rather than a threatening encounter to be avoided (15 of 36; 2 users could not be assigned to either category).

These adaptation processes and strategies may be related to uncertainty factors within the range experience that were a predominant experience feature as reported by users (10 of 36). The users conceived that range resources were dependent upon factors that both the EV and users themselves could not predict. This uncertainty about remaining range was a central aspect of the user experience that users only seldom resolved with an accurate mental model of the system.

3.2 Quantitative Indicators of Range Experience

Concerning range satisfaction, 90 per cent of experienced users agreed (dichotomisation of 6-point scale item) that the range offered by the EV was sufficient for everyday use while they also stated that they would be able to do most trips (M = 93%, SD = 8.25) with the EV if the biggest usage barriers beyond range, limited passenger and cargo space (i.e. car was two-seater with very small trunk), were removed (both items at T1). Hence, range-related mobility resources were perceived as sufficient for most users.

An analysis of range concern indicators administered at T1 showed that a majority of users (82%) agreed with the statement that they were more worried about range when driving an EV compared to a conventional ICE vehicle (M = 4.54, SD = 1.47), but only 12 per cent agreed that they often worried about range (M = 2.31, SD = 1.15) while driving. This result was also supported by two items administered at T2 that asked how often per month users experienced stressful range situations over the whole trial. Users reported a mean frequency of 1.09 (SD = 1.53) events per month where they encountered a range-related stressful situation. Dividing frequency ratings into four categories, 34 per cent of users never experienced such a situation, 18 per cent experienced it at least once but less than once a month, 24 per cent of the users indicated once a month, and 24 per cent felt stressed more than once a month due to range. Results for the second item, becoming nervous because of range, resulted in a mean frequency of 1.24 (SD = 2.13) events reported per month (four computed frequency categories: 32%, never; 24%, at least once but less than once a month; 26%, once a month; 18%, more than once a month). Thus, although range worries increased in EVs compared to conventional ICE vehicles, phenomena similar to the previously reported range anxiety were not frequently reported among the drivers. This could be because users adapt to range (i.e. avoid stressful situations) or because users simply do not have the mobility needs that approach a critical level in terms of the mobility resources that an EV offers.

Analysis of the four variables indicative of facets of comfortable range resulted in sizeable inter-individual variation within the sample of the 32 users that had no missing values in any of the variables later used in the regression analysis. Score values for maximum comfortable trip distances per charge were from 80 km to 165 km ($M = 130.0$ km, $SD = 22.0$, $Q_{25} = 115$, $Q_{75} = 150$). These results are indicative of suboptimal range utilisation in terms of cycle range, as well as in relation to the given range of 168 km communicated by the EV manufacturer as realistic for everyday driving (i.e. performant range). Similarly, users stated that they reserved a safety buffer of $M = 19.2$ km displayed remaining range ($SD = 15.3$ km, $Q_{25} = 10$ km, $Q_{75} = 25$ km) below which they would not (except in exceptional circumstances) use the EV. In the range game, users' range comfort zone (i.e. threshold where users no longer felt perfectly comfortable with the remaining range) was reached on average when remaining range displayed was 73.2 km facing the 60 km trip distance to the next charging opportunity ($SD = 11.1$, $Q_{25} = 65.6$, $Q_{75} = 80.6$). The range threat appraisal, referring to the situation in which remaining range and remaining trip distance were equal, resulted in an average scale value of 3.66 reported by users on the 6-point scale ($SD = 1.29$). Here, once again, variation in appraisal scores was substantial (min = 1.25, max = 5.75). Overall, our data show that users were neither willing nor comfortable using the full range resources of the EV, and preferred to plan trips with substantial range buffers with sizeable inter-individual variation in comfortable range.

Inspecting differences between variables, absolute comfortable range buffers assessed by the range game were smaller than those assessed by the maximum comfortable trip distance. A possible reason for this could be that the relatively low level of ambiguity and risk in the range game situation (e.g. conditions of the trip are clear) reduced range discomfort while the high ambiguity due to the long trip distance (e.g. higher potential range variation) in the maximum comfortable trip distance variable is related to larger buffer values. It could also be that users reserve a proportional range buffer, as they were willing to utilise around 80 per cent of range resources in both variables (i.e. driving 130 km with 168 km range and 60 km with 73 km range).

To examine the relation of the four variables and to yield a composite score for comfortable range for the regression analyses, an exploratory factor analysis using the principal axis method was conducted. For this and all subsequent analyses the four variables were z-standardised and inverted to high numerical values indicating high comfortable range, as necessary. A single-factor solution resulted from this analysis, both according to Kaiser criterion (eigenvalue of first factor = 2.17, second factor = 0.88) and scree plot. All variables had acceptable factor loadings (range threat appraisal = .62, range game comfort zone = .70, maximum comfortable trip distance = .52, range safety buffer = .67). Assessing the internal consistency of the z-standardised values of the four variables, a Chronbach's alpha of .72 was obtained. For the composite comfortable range variable a factor score for each user was derived from the principal axis analysis (regression method).

3.3 Personal Resources and Comfortable Range

Three multiple linear regression analyses were conducted to examine the role of stress-buffering traits and coping skills in comfortable range: (1) personality trait model, that tests the role of control beliefs and ambiguity tolerance in comfortable range; (2) coping skill model, that examines the role of subjective range competence and daily range practice; and finally (3) composite model, that tests the contribution of stress-buffering personality traits versus coping skills in explaining comfortable range.

As a prerequisite for the analyses we examined whether the 13 assumptions for multiple regression analysis were met according to Stade, Meyer, Niestroj, and Nachtwei (2011). For all three analyses, assumptions were sufficiently met: Linear relationships between all predictors and the criterion could be assumed (p-values < .05 for linear model fit; F-value for linear greater than for quadratic model fit, for every predictor). There was sufficient variance within the predictor and the criterion, individual values of the criterion were independent, all variables were sufficiently reliable (see above), a univariate normal distribution could be confirmed (p-values for Kolmogorov-Smirnov tests all > .67) and multicollinearity was found to be very weak (all VIF < 1.2). Autocorrelation within the residual was judged still acceptable (Durbin Watson test 1.07 to 1.56, 1.38 to 1.64 when outliers were excluded), homoscedasticity of the residuals could be assumed (p-values for Levene tests > .44) and a normal distribution of residuals was indicated (p-values for Kolmogorov-Smirnov tests > .77). There were no influential cases (maximum Cook's D < 0.26), but one extreme outlier case for all three analyses ($z = |2.40|$ to $|2.88|$) and another outlier case for the coping-skills regression analysis ($z = |2.25|$) was obtained. In the following, results are given with ($N = 32$) and without ($N = 30$ to 31) these outliers. After excluding these outlier cases no new outlier cases emerged. This sample size was evaluated as just sufficient for testing two predictors in one analysis assuming strong effects ($R^2 = .26$) and desired statistical power of .8 (power calculation with G*Power; Faul, Erdfelder, Buchner, & Lang, 2009).

Correlation coefficients for the variables in the regression analyses are depicted in Table 1. Correlations within the two classes of predictor variables, trait versus skill variables, and between the two groups were weak to

TABLE 1
Correlation Coefficients for Variables Included in the Regression Analyses

		1	*2*	*3*	*4*	*5*	*6*	*7*
1	Control beliefs	–						
2	Ambiguity tolerance	.33	–					
3	Subjective range competence	.49**	.24	–				
4	Daily range practice	.07	−.03	.24	–			
5	Personality trait composite	.82**	.82**	.45*	.02	–		
6	Coping skill composite	.35*	.13	.79**	.79**	.30	–	
7	Comfortable range	.47**	.39*	.48**	.39*	.53**	.55**	–

Note: $N = 32$; * $p < .05$; ** $p < .01$ (two-tailed)

TABLE 2
Personality Traits and Coping Skills as Predictors of Comfortable Range

	B		SE *B*		β		p		*Part correlation*	
Personality trait model										
Constant	−3.27	*−3.23*	0.97	*0.83*						
Control beliefs	0.45	*0.44*	0.19	*0.16*	.39	*.43*	.014	*.006*	.37	*.41*
Ambiguity tolerance	0.29	*0.30*	0.18	*0.15*	.26	*.31*	.062	*.032*	.25	*.29*
Coping skill model										
Constant	−2.36	*−2.05*	0.92	*0.75*						
Subjective range competence	0.56	*0.51*	0.22	*0.18*	.41	*.46*	.010	*.004*	.40	*.44*
Daily range practice	0.28	*0.26*	0.15	*0.13*	.29	*.32*	.035	*.024*	.29	*.31*
Composite model										
Constant	0.00	*0.06*	0.12	*0.10*						
Personality trait composite	0.49	*0.52*	0.18	*0.15*	.40	*.48*	.005	*.001*	.38	*.46*
Coping skill composite	0.60	*0.50*	0.20	*0.17*	.43	*.40*	.003	*.004*	.41	*.38*

Note: Results after outlier exclusion are given in italics; $N = 32$ for total sample; $N = 31$ (personality trait model, combined model), $N = 30$ (coping skill model) without outlier cases; *p*-values are one-tailed.

moderate except for the correlation between control beliefs and subjective range competence that yielded almost a strong effect size. All predictor variables were moderately to highly correlated with the criterion variable being comfortable range.

The forced entry method was used for the regression analyses (for detailed results see Table 2). As we had directional hypotheses for the effects of the individual predictors, these tests were one-tailed (two-tailed for omnibus tests of whole model fit R^2). As to the positive role of the two personality traits of control beliefs and ambiguity tolerance, an adjusted R^2 = .24 was obtained ($F(2, 29) = 5.82$, $p = .008$) with control beliefs having stronger impact on the model than ambiguity tolerance. Excluding the outlier case, the value for R^2 increased to $R^2 = .32$ ($F(2, 28) = 8.13$, $p = .002$) with both predictors yielding a significant and at least nearly moderate effect. Similarly, the coping skill model with subjective range competence and daily range practice as predictors yielded an adjusted R^2 =.26 ($F(2, 29) = 6.53$, $p = .005$). Both predictors turned out to reliably contribute to the model with subjective range competence showing a stronger association with comfortable range than daily range practice. Again, excluding the two identified outlier cases led to an increase in explained variance (adjusted R^2 = .34, $F(2, 27) = 8.45$, $p = .001$). To examine the relative contribution of personality traits and coping skills in comfortable range, factor scores were computed from the two predictor variables in each of the two variable classes. These two composite scores then entered the analysis. An adjusted $R^2 = .42$ was obtained ($F(2, 29) = 12.00$, $p < .001$). Both composite variables turned out to be reliable predictors of comfortable range. Again, excluding the outlier case improved the model fit, adjusted $R^2 = .47$, $F(2, 28) = 14.49$, $p < .001$. Hence, for both personality traits and coping skills, a substantial, yet distinct, role in comfortable range was indicated. All in all, a substantial share of the variance in comfortable range could be explained by the hypothesised predictor variables.

4 GENERAL DISCUSSION

The present research investigated how EV range is experienced by experienced drivers. Qualitative dimensions as well as quantitative indicators were examined and the role of personal resources in comfortable range was assessed. We found that range is a central resource in interacting with electric mobility systems. While range is broadly considered a major barrier to EV acceptance, a major finding of the present research was that experienced users subjectively appraised range as a resource that they could successfully adapt to. They obtained high range satisfaction and finally perceived that they could satisfy most daily mobility needs with the EV. Moreover, from the present study it can be concluded that range anxiety is not very prominent in EV use. Most users rarely ran into situations where they felt stressed or nervous as a result of range. Although users worried more about range than they would have in a conventional car, these worries occurred relatively infrequently. According to the results of the qualitative analysis, users experienced range somewhat more like a problem-solving task rather than as a stressful encounter. Since the mobility patterns of the users (assessed using data loggers in EVs) was relatively similar to users of comparable ICE vehicles (Keinath & Schwalm, 2010), it is likely that this finding not only applies to the present study in urban Berlin, but also to several other contexts. Nevertheless, certain contexts that require, for example, long daily commutes or do not provide sufficient private charging opportunities may challenge this appraisal. In summary, it seems reasonable to conclude that for many users, range in electric mobility is manageable in its current stage of development. However, in terms of true environmental utility, cost-effectiveness and broad market potential, EV range not only has to be accepted by users, it also has to be experienced in a way that promotes efficient use of this precious resource.

Substantial inter-individual differences were found in comfortable range and range appraisal variables within the user group. The results indicate substantial differences in the range buffers users set themselves and, notably, suboptimal range utilisation for many users. Of course, low range utilisation in the field may also be a result of low mobility needs, but the questionnaire items in the present study controlled for such confounding variables. Moreover, in qualitative reports, users described trips they would have liked to have made but were not able to or comfortable with, because these trips represented borderline range situations. Hence, evidence suggests that comfortable range and range utilisation should be enhanced in present and future electric mobility systems. Yet, enhancing potential range utilisation requires a comprehensive understanding of relevant factors that users include in their personal equation for comfortable range.

Concerning the dynamics of comfortable range, we found similarities to dynamics of experiencing stressful encounters. Measures for range appraisal and comfortable range were related to protective factors known to affect stress experience. Evidence shows that internal control beliefs and ambiguity tolerance have moderate stress-buffering effects in terms of range appraisal and comfortable range. Users that scored low on these variables, in particular, would require support to achieve a high level of range utilisation. Moreover, as Lazarus points out in his work on stress (Lazarus & Folkman, 1984), compared to situational beliefs, general personal beliefs influence appraisal more intensely in ambiguous situations than in unambiguous situations. Thus, a tentative conclusion may be that the obtained effects concerning personality traits might also suggest a particular need for working on disambiguating range situations, for instance, with improved human–battery interfaces. In addition to the stress-buffering effects of personality traits there was also evidence for substantial stress-buffering effects of coping skills. Subjective range competence, that is, positive belief in one's ability to mentally model range and range-influencing factors, was positively linked to enhanced range appraisal and comfortable range. Moreover, it was found that daily range practice was positively related to comfortable range. This last group of variables points to the potential of information and training on users' range utilisation and range experience.

In sum, the protective variables examined proved fruitful in advancing our understanding of the dynamics of range appraisal and comfortable range.

4.1 Implications for the Future Development of Electric Mobility Systems

The results of the present study suggest that successful electric mobility systems should not only incorporate an EV and charging infrastructure, but also a formal attempt to cope with central human factor issues, one of these being range. Daily range practice with an EV is related to range appraisal. Hence, the range barrier experienced by many novices may be successfully overcome by practice in dealing with range. As a first step, a highly accessible intervention for users would be to simulate their daily mobility behavior, for example, using a travel diary. Also, in the present study's interviews at T0, before users received the EV, participants reported that using a diary improved their optimism regarding an estimate of the fit between their mobility needs and the range resources presented to them; for the first time, they discovered what a high percentage of their trips an EV could be used for. In the same vein, an experienced user reported that practice with driving the EV made him more accurate in judging distances. When at first he estimated a certain trip distance at 10 km, he later learned that it was actually shorter (e.g. 6 km). Ideally, a range-barrier intervention would also incorporate personality variables such as general control beliefs to define individually based levels of support needed. Development of comprehensive training and feedback loops, for example, incorporating competitive elements, could be promising as well.

The present findings also have implications for advancing the traditional core of electric mobility systems. Fallback options, in terms of recharging opportunities and supportive design of human–machine interfaces, can reduce ambiguity and increase internal situational control beliefs, for example, incorporating information related to confidence in displayed remaining range estimations or adding navigational references (Neumann, Cocron, Franke, Bühler, Wege, & Krems, 2010). Adaptive assistance and information systems (in terms of remaining range situation and personal variables) could increase the impact of such designs even further. However, such improvements could also lead to some form of negative behavioral adaptation resulting in users acquiring less range skills (i.e. lower competent range) and developing less energy-efficient driving habits (i.e. lower performant range), which in turn would reduce comfortable range. This phenomenon has been discussed in the research on driver-assistance systems (Young, Regan, Triggs, Jontof-Hutter, & Newstead, 2010) and has been related to theories of risk and task-difficulty homeostasis (Fuller, 2005; Wilde, 1982). Such aspects should receive further attention in future studies.

A potential criticism concerning the present study may be whether research on psychological factors involved in interacting with range in EVs is of value, because development of battery technology and charging infrastructure density and performance (e.g. battery swapping stations) will ultimately make range-barrier considerations redundant in the coming years. In fact, EVs currently in development offer ranges suitable to a majority of the mobile population, when considering range resources and mobility needs, in general. However, the costs of such range setups still far exceed the prices that car buyers are willing to pay for an EV. In addition, as indicated for example by the difference in range buffers of short and long distances, greater ranges (trip distances) may also result in higher range buffers. Thus, the problem of low range utilisation may increase.

Taken together, it is important to understand factors that increase the efficiency of EV range use, as well as the accompanying stressfulness of such range utilisations. This is the basis for discovering feasible approaches to enhancing usable range for electric mobility users. Based on the current findings, instead of simply maximising range, it may be more desirable to offer reliable and affordable range setups that meet perceived mobility needs or, more specifically, that result in a reasonably high comfortable range.

5 CONCLUSIONS

The range of EVs has long been considered a major barrier to public acceptance of electric mobility. However, for state-of-the-art electric mobility systems our evidence suggests that range is primarily a psychological barrier. However, this does not imply that range in electric mobility systems can be dismissed, especially if we take environmental utility and pricing issues into consideration. The present study attempted to broaden as well as shift the focus of conventional research, from increasing nominal battery capacity to focusing on enhancing usable range. Understanding individual range experience dynamics and proposing ideas for supportive interventions were efforts in this direction.

To support the feasibility of this approach, we introduced a relevant variable for range experience—comfortable range—merging variables discussed in previous research, namely, range buffers and range anxiety. This proposed variable was contextualised in four psychological range levels. We present a first attempt to theoretically define the variable of comfortable range within the broader theoretical framework of stress and general control theory. Viable strategies to improve range experience may be devised from this outline, to ensure the successful development of future electric mobility systems.

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III Artikel 2: Interacting with limited mobility resources: Psychological range levels in electric vehicle use

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Interacting with limited mobility resources: Psychological range levels in electric vehicle use

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ABSTRACT

Limited driving range is an obstacle to adoption of electric vehicles (EVs). We examine from a self-regulation perspective the psychological dynamics underlying individual reference values for three different types of range constructs. In a 6-month field trial 40 EVs were leased to a sample of early adopter customers. In general, users were satisfied with range and stressful range situations rarely occurred. Results further suggested that users were comfortable with utilizing approximately 75–80% of their available range resources. Several personality traits (e.g., control beliefs, low impulsivity) and system competence variables (e.g., daily practice, subjective competence) were positively related to range level values and thus range utilization. Comfortable range was positively related to range satisfaction. We recommend that psychology-based strategies should be applied to enhance range optimization.

1. Introduction

Increasing concerns about the environmental impact of the current road transport system as well as the risks associated with peak oil (Hirsch et al., 2005) have stimulated interest in electric mobility systems[1] (EMSs). Battery performance and cost-effectiveness are still major barriers preventing the broad adoption of electric vehicles (EVs) (International Energy Agency, 2011).

Mobility resources in EMSs are more limited and precious compared to those of combustion-powered mobility systems (CMSs) and will likely remain so in the near future (Boston Consulting Group, 2010). Mobility data nevertheless reveal that the currently common 100-mile range of EVs would objectively satisfy the needs of many car drivers (Pearre et al., 2011). Nevertheless, car drivers typically perceive range as a barrier for considering EV use (Dimitropoulos et al., 2011). Research findings indicate that experience with an EV may reduce such range concerns and leads to higher range satisfaction (Franke et al., 2012b; Nilsson, 2011). This comes however at the expense of non-optimal range utilization, that is that users tend to avoid critical and potentially stressful range situations planning for substantial range buffers (Caroll, 2010; Franke et al., 2011). For example, users are only willing to utilize 80% of their available range (Franke et al., 2011). Range buffers are also likely present in conventional internal combustion engine (ICE) vehicles. Yet, range buffers are more relevant for EV use as each kWh of battery capacity should be translated into accessible range to enhance market potential and environmental utility of EVs.

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[1] With EMS/CMS we refer to a certain configuration of a vehicle (range and possible charging/refueling duration) and the available charging/refueling infrastructure (public vs. private, network density, usual available charging/refueling speed) as both parts together constitute the mobility resources available.

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Our research aims to increase understanding of factors that influence users' range utilization behavior. We propose three range levels termed competent, performant, and comfortable range. They drive the transition from a technically maximum possible range to a practically usable range. We apply concepts of self-regulation and control theory (Carver and Scheier, 2001) to better understand inter-individual differences within these three range levels. We test the explanatory power of variables known to be important for self-regulation from related domains. To this end, we conducted a 6-month field trial with 40 EVs leased to volunteer drivers. During this field trial, we examined: (1) range experience and indicators of range utilization, (2) the relation of personality traits and system competence variables to range level values, (3) the relationships between the different types of range levels, and (4) the relation of range levels to range satisfaction.

1.1. The adaptive control of range resources framework

Fig. 1 illustrates how we conceptualize users' management of EV range resources as a control task aimed at maintaining certain preferred states (e.g., staying within personal range comfort zone) which translate into individual reference values (e.g., comfortable range level). These reference values are regulated by individual (e.g., range competence) as well as environmental factors (e.g., route profile). This dynamic interplay leads to an individual efficiency level of range utilization for each user.

Imagine the following example: for a trip an EV user chooses between the EV and another household vehicle. The available range (i.e., mobility resources) is estimated to be 60 km and the total journey distance (i.e., mobility needs) 50 km. That leads to a perceived range buffer of 20%. We propose that users' appraisal of such a situation depends on several factors, in particular their preferred range safety buffer (i.e., comfortable range). Range safety buffers in turn will be affected by coping skills, such as practice with EV range or self-concepts of competence in dealing with range, as well as by personality traits such as general control beliefs. This process may be fast and automatic if available and preferred range buffers differ considerably. Otherwise it may be deliberate such that users carefully evaluate their options for extending range, for example, by applying energy-efficient driving strategies. For this evaluation, users have to relate the currently available range to their average (i.e., performant) and maximum (i.e., competent) range values. Based on this appraisal (i.e., situation model), users will adapt their range-related behavior (i.e., coping strategies), for example, by adjusting trip decisions, planning for emergency charging spots and other fallback options, energy-efficient driving, adapting different driving and charging styles to increase future safety buffers or actively improving range management skills. Feedback from the environment (e.g., development of available range buffer during a trip) provides users with information on the success of their strategies, which in turn modifies the representation (i.e., the mental model) of the reference values.

Principles of control theory and self-regulation (Carver and Scheier, 2001) have been applied to a wide range of phenomena. Inter-individual differences in variables such as personality traits and competencies determine successful (adaptive) self-regulation (Boekaerts et al., 2005; Hoyle, 2010). Reference values (i.e., individual standards and goals) are central components in the control loop (Baumeister and Heatherton, 1996). We have introduced three psychological reference values that regulate the efficiency of range utilization: competent, performant, and comfortable range. First, we assume that users differ in their self-set standards for developing competency for understanding range dynamics and extending range. These individual standards translate into their maximum achievable, and hence competent range. This value will likely be lower

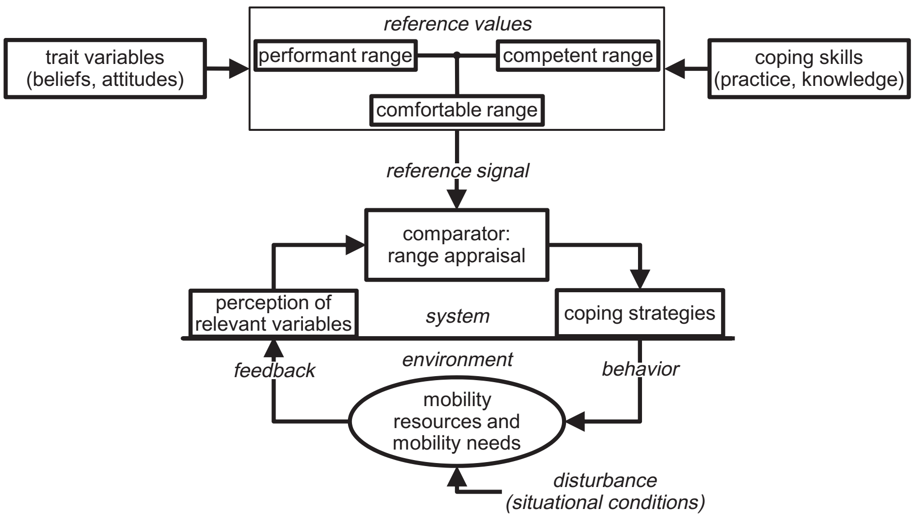

Fig. 1. The adaptive control of range resources framework. Users compare the current range situation with their range level reference values. These are in turn driven by certain trait and coping skill variables. As a result of this comparison coping strategies are adapted (e.g., drive more economically, do not use EV). This leads to a certain efficiency of range utilization.

than the maximum range technically possible because users face limits in their self-regulation capacity. Second, achieving competent range requires considerable self-regulation resources (e.g., continuous monitoring of range dynamics in relation to implemented actions). Moreover, energy efficiency is only one goal when driving a car. Thus, users will likely achieve lower range values in everyday use. We term this average range performant range. Third, users hardly use the entire available range (e.g., competent or performant). Based on previous findings (Franke et al., 2011), we hypothesize that users adopt an individual range comfort zone that translates into a certain preferred range safety buffer, based on individual standards for avoiding stressful situations. We refer to this level as comfortable range. In sum, all three levels contribute to the gap between technically feasible and actually usable range.

Given the complexity of user–range interaction, we expect substantial variations in the reference values: (1) while adapting to limited range, (2) due to situational conditions, and (3) due to individual user differences. In this paper we focus on examining the third aspect, inter-individual differences between EV users that are already adapted to EV range. In our field trial we control for situational variation as far as possible in such a setting. In the following, we describe the three range levels and the factors explaining inter-individual differences in range level values in more detail.

1.1.1. Competent range

The impact of user behavior on EV energy consumption is more complex and characterized by different dynamics than those in ICE vehicles (e.g., concerning efficient use of regenerative braking, auxiliary consumers like heating, light, etc.) (Romm and Frank, 2006). Achieving optimal energy efficiency requires substantial perceptual, cognitive, and motor resources (e.g., monitoring range dynamics, systematic test of range extension strategies). Operators have been found to experience difficulties performing similar control tasks in equally complex dynamic environments (Frensch and Funke, 1995; Osman, 2010). Furthermore, users differ in their achievement motivation or goal orientation (Pintrich, 2000). Both, competence beliefs as well as feedback on maximum performance contribute to the development of a self-concept of competence (Bandura, 1977; Boekaerts, 1991; Weinert, 1999). This in turn translates into a reference value of competent range, which is the maximum range a user is able to achieve. We thus operationalize competent range as the maximum range displayed after a full charge, given previous maximum range-optimizing efforts.

Among personality trait variables, internal control beliefs, that is the degree to which people believe that they can control events that affect them (Rotter, 1966), have been linked to more successful self-regulation (Bandura and Wood, 1989). Moreover, individuals with a higher need for cognition, that is the tendency to enjoy complex information processing demands (Cacioppo and Petty, 1982), are more efficient and successful in complex problem solving (Nair and Ramnarayan, 2000). Impulsivity, that is the tendency to control and plan insufficiently, is usually linked to low self-control and lack of persistence (Hoyle, 2010). High impulsivity interferes with reaching long-term goals (Carver, 2005) and problem-solving tasks that demand a high level of planning (Pietrzak et al., 2008). Tolerance of ambiguity, that is the tendency to experience ambiguous stimuli as desirable and challenging instead of threatening (Furnham and Ribchester, 1995), is an important factor for successful learning (e.g., Chapelle and Roberts, 1986) and self-regulation in creative problem solving tasks (Stoycheva, 2003). We expect internal control beliefs, need for cognition, low impulsiveness and tolerance of ambiguity to be positively related to competent range.

Among system competence variables, prior knowledge facilitates successful self-regulated learning (Moos and Azevedo, 2008) and affects performance in problem-solving environments positively (Lee and Chen, 2009). Subjective competence leads to more effort investment, and in turn, independent learning (Boekaerts, 1991). Moreover, the closely related concept of self-efficacy is important for gaining knowledge and setting challenging goals (e.g., Zimmerman et al., 1992). Finally, daily practice has been identified as key for promoting self-regulatory skills (Zimmerman and Kitsantas, 2005). Based on these findings, we expect prior knowledge of EV technology, subjective competence in dealing with range and daily range practice to be positively related to competent range.

1.1.2. Performant range

Optimizing vehicle range demands substantial self-regulation resources and is only one goal when driving a car besides a fast and comfortable journey and enjoying acceleration performance. Hence, in everyday driving most users will obtain range values below their competent range. We term this range performant range: the average or typical available range based on user's driving motives and habits. Performant range is indicated by the displayed range when the EV is fully charged.

Among personality variables driving style is essential as it reflects relatively stable habits, general attitudes, needs, and values (Elander et al., 1993), as well as lifestyle attributes (Møller and Sigurdardóttir, 2009). Notably speedy and aggressive driving style should be linked to performant range because speed and acceleration are closely related to energy consumption in EVs. Furthermore, the willingness to take risks in driving is related to a higher probability of speeding and of reckless driving (Hatfield and Fernandes, 2009). Thus we expect speedy driving style and risk propensity in driving to be negatively associated with performant range.

1.1.3. Comfortable range

We define comfortable range as the preferred range safety buffer of a user, that is the range buffer that is experienced as not stress-inducing (i.e., enough to avoid range anxiety). This range safety buffer can be expressed in absolute values (e.g., always keep a 10-km range reserve), relative values (e.g., 20% reserve), or minimum values (e.g., never go below 10 km remaining range). Range buffer values can be assessed directly by asking users to provide such values, or indirectly by assessing the experienced stressfulness of certain range buffers.

We assume that comfortable range is a function of performant and competent range, as well as individual characteristics relevant for coping with uncertain, demanding and stressful situations. Thus, comfortable range is most relevant for range appraisal as it reflects the perceived balance between mobility needs (e.g., journey distance, route profile, trip purpose) and mobility resources (e.g., remaining range, competent range, dispositional resources). Maintaining a certain comfortable range is similar to stress regulation which has also been described with control theoretic models (Edwards, 1992; Lazarus and Folkman, 1984). These models assume that stress is the result of a perceived imbalance between the demands that arise from a person's environment or his or her desires and the available resources that the person possesses. In a circular process people appraise and regulate this balance. These models also highlight the key role of individual differences in stress-buffering variables which moderate the appraisal process (Connor-Smith and Flachsbart, 2007).

Among personality traits, internal control beliefs have been addressed extensively as stress-buffering variables in the original work of Lazarus and Folkman (1984) and in research on driver stress (Holland et al., 2010). Ambiguity tolerance has been linked to less avoidance of uncertain (i.e., potentially stressful) situations and reduced experienced stress in ambiguous situations (Frone, 1990; Furnham and Ribchester, 1995; Lazarus and Folkman, 1984). In contrast, high impulsiveness is related to a tendency to avoid unpleasant or difficult tasks (Carver and Connor-Smith, 2010). Lack of planning and low self-control as aspects of high impulsivity should also exert a negative effect on comfortable range. Accordingly, we expect internal control beliefs, ambiguity tolerance and low impulsivity to be positively related to comfortable range.

With regard to system competence variables, effective coping strategies promote stress resistance. Subjective competence and self-efficacy have been related to stress resistance (Bandura, 1977), notably the tendency to interpret demands as challenges rather than as threats (Zajacova et al., 2005). Also, practice with technical systems (Holland et al., 2010) results in less stress experience. Thus, we expect subjective competence in dealing with range and daily range practice to be positively related to comfortable range.

1.2. Research objectives

We argue that models of self-regulation and related research in problem-solving, learning, driving style, and stress offer valuable perspectives on the psychological dynamics of EV range utilization. We propose that investigating individual differences in the reference values of comfortable, performant, and competent range will enhance our understanding of range utilization.

In the present research we first examine users' general range experience (e.g., range satisfaction, frequency of critical range situation), as well as comfortable range variables indicating range utilization. Second, we analyze individual differences in comfortable, performant, and competent range. For all three range levels we investigate the impact of several personality traits (control beliefs, need for cognition, ambiguity tolerance, impulsiveness, driving style, risk propensity in driving) and system competence variables (prior knowledge, daily practice, subjective competence) on users' reference values. We expect to find a positive relation of internal control beliefs, ambiguity tolerance, and low impulsiveness with comfortable and competent range; a positive relation of need for cognition to competent range; and a negative relation of speedy driving style and risk propensity in driving to performant range. We expect a positive relation of daily practice and subjective range competence to comfortable and competent range, and of prior knowledge to competent range. We also test the relation of performant and competent range to comfortable range, where we expect positive relationships for both variables to comfortable range. Third, we examine which range level variables are associated with the outcome measure of range satisfaction. We expect positive relationships between range levels and range satisfaction.

2. Method

2.1. Field trial setup

The present research was part of a large-scale EV field trial in the metropolitan area of Berlin, Germany. This trial was set up by the BMW Group and Vattenfall Europe, and funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. It was part of an international EV field trial (Vilimek et al., 2012). The EV was a converted MINI Cooper with a maximum cycle range of 250 km under ideal and 168 km under normal driving conditions (miniusa.com, 2012). It was equipped with a state-of-charge display and a remaining-range display (km), based on consumption over the last 30 km. Test drivers had access to a network of 50 public charging stations in the metropolitan area of Berlin, as well as to a private home-based charging station (4 h full charge duration). In the field trial two consecutive 6-month user studies were conducted. This paper incorporates data of the second study ($n = 40$). Participants used EVs between end of February and end of August 2010. For each user, data were collected prior to receiving the EV (T_0), after 3 months of driving (T_1), and upon returning the EV after 6 months (T_2). At each point of measurement, users filled out a 1-week travel diary, and took part in a 2- to 3-h face-to-face interview including completing several questionnaires. A wide range of topics was covered using a multi-method approach that allowed for data triangulation and data fusion. Logger data were recorded by the car manufacturer and were related to subjective data through personalized keys. Further details on the field trial methodology are reported elsewhere (Cocron et al., 2011; Franke et al., 2012a). This trial setup aimed at controlling situational variations (e.g., vehicle load, climate, terrain, traffic conditions) on user–range interaction.

2.2. Participants

Forty participants were selected from 489 applicants recruited via an online screening instrument that was announced in newsprint and online media. Requirements for participation were residence in the Berlin metropolitan area, willingness to pay a monthly leasing rate of 400 Euro (about the same as for an equivalent gasoline model with similar leasing conditions[2]), to take part in a scientific study, and to install a private home-based charging box. Further criteria aimed to ensure considerable variance in basic socio-demographic variables (e.g., age, gender, education) and mobility-related variables (e.g., mileage, vehicle fleet). Only the main EV user from each household was included in the data collection. As recruitment criteria were comparable to current EV leasing criteria (e.g., monthly leasing rate, access to charging facility), we expect the sample to be representative for early adopters of EVs in German urban areas. The 40 participants had a mean age of 50 years ($SD = 10.2$), 35 were male, and 29 had a university degree. All participants' households had access to at least one additional conventional car during the trial.

2.3. Personality trait measures

Personality trait measurements used a 6-point Likert scale and response coding of 1–6 unless specified otherwise. We used the 8-item internal control beliefs in dealing with technology scale of Beier (1999), the 8-item ambiguity tolerance scale of Dalbert (1999), the "speed" scale of the driving style questionnaire (DSQ, French et al., 1993) with three items and a 6-point frequency scale, and the need for cognition scale (Bless et al., 1994) with 16 items and a 7-point Likert scale from −3 to +3. For risk propensity in driving and impulsivity we used two single-item measurements from the German socio-economic panel (Siedler et al., 2008). Both items employed an 11-point Likert scale (0–10). Due to missing values, there were between 37 and 39 valid cases per trait variable. We tested for univariate outliers according to the procedure and thresholds proposed by Grubbs (1969) for all variables. For personality traits, one outlier was detected for control beliefs (z-value = −3.17) and was therefore excluded. All multi-item measurements yielded a satisfactory reliability with Cronbach's alpha > .70.

2.4. System competence measures

2.4.1. Subjective range competence

We assumed that subjective EV range competence would be driven by feelings of confidence in predicting remaining range as well as feelings of control over range-influencing factors. Accordingly, these two facets were addressed with two items each. For prediction "I know how far I can go on a full charge," and "I can precisely estimate the influence of different factors on range", and for control "The range of my EV is mostly affected by factors over which I have no influence," and "The range that I can reach with my EV is mostly dependent on factors that I can control". A 6-point Likert scale ranging from 1 (completely disagree) to 6 (completely agree) was used for these and all other self-constructed agreement ratings. There were two cases with missing values and one outlier ($z = -3.75$, $n = 37$). Reliability was only partially satisfying with Cronbach's alpha $T_{1\text{all4}} = .50$, $T_{1\text{control2}} = .39$, $T_{1\text{prediction2}} = .50$, $T_{2\text{all4}} = .74$, $T_{2\text{control2}} = .67$, and $T_{2\text{prediction2}} = .49$. To increase reliability we averaged scale values at T_1 and T_2 supported by a strong positive correlation of values between T_1 and T_2 ($r_{\text{all4}} = .67$). The reliability for the combined item values was acceptable with Cronbach's alpha $T_{12\text{all4}} = .76$, $T_{12\text{control2}} = .67$, $T_{12\text{prediction2}} = .59$. In a factor analysis items loaded primarily on the control and prediction factor as expected although with some sizeable cross-loadings.

2.4.2. Prior knowledge of EV technology

At T_0 users were asked to rate their familiarity with three aspects of EV technology on a standard 6-point Likert agreement scale: EV drivetrain, units of electricity, and different types of batteries. There was one missing value and no outlier ($n = 39$, Cronbach's alpha = .85).

2.4.3. Daily range practice

We assumed that both frequency of range considerations before a trip (e.g., trip planning) and exposure to dealing with range during a trip (e.g., experiencing range dynamics, improving skills) constitute daily range practice. Therefore we combined in one indicator variable the mean daily number of trips ($M = 3.12$, $SD = 1.07$, no outlier) and the mean daily distance driven with the EV ($M = 41.46$ km, $SD = 18.86$, one outlier with $z = 3.24$) taken from T_1 travel diary (5 workdays only). There were seven cases with missing values in the combined daily range practice score ($n = 32$, Cronbach's alpha = .43).

[2] The leasing rate of the EV without taking part in the scientific study was said to be 650 Euro.

2.5. Range measures

2.5.1. Competent range measures

For competent range a composite score was constructed consisting of subjective and objective subscores to provide comprehensive information on users' maximum achievable range. The objective subscore was defined as maximum displayed range when fully charged recorded by data loggers in the EV. The logger data recorded the range displayed at the beginning of each trip throughout the study period. Those values were included that could be related to the main user, that referred to periods with moderate temperatures of 5–25 °C, and that did not refer to the first 2 months of use, as we were only interested in range level values of adapted drivers. Values that referred to situations with the battery not fully charged were extrapolated to full charge range. From these range values we extracted the maximum value as the objective subscore for competent range.

For the subjective subscore we asked participants about their maximum trip distance with four items: maximum accomplishable trip distance, maximum distance with all factors optimized, potential trip length in an urban area under optimal conditions, and perceived maximum range ever displayed. A factor score was computed from the first factor of a principal-axis factor analysis (eigenvalue = 2.38, second factor = 0.82, all factor loadings >.37). One outlier was detected ($z = 3.10$) on this subscore.

The subjective and objective subscore z-values yielded a Cronbach's alpha of .50 and were joined with a factor score to yield the final criterion variable for competent range. Because of missing values $n = 35$.

2.5.2. Performant range measures

For performant range we combined subjective and objective subscores to include information on users' average and typical available range. The objective subscore was defined as the mean displayed range of the fully charged EV, as recorded by data loggers in the car (scored in parallel to competent range).

The subjective subscore consisted of three items: "Which displayed range does the EV currently have for you when it is fully charged? (in normal daytime temperatures of approx. 10–20 °C)" and "Please indicate, based on your experience, the range that was displayed after a full charge when daytime temperatures were: (a) approx. 10 °C and (b) approx. 20 °C". There was one outlier with values outside the plausible range of values (e.g., 10 km available range) that was excluded. A factor score was computed for the first factor (eigenvalue = 2.44, second factor = 0.41, all factor loadings >.70).

Objective and subjective subscore z-values yielded a Cronbach's alpha of .58, and were combined to yield the final composite criterion variable for performant range (factor score). Because of missing values $n = 35$.

2.5.3. Comfortable range measures

The composite variable of comfortable range incorporated three subscores. First, the range game assessed the individual range comfort zone in a standardized, ecologically valid scenario (60-km trip in a mostly urban area). Four items asked participants to report their comfort level for embarking on a trip. This was done 10 times with displayed range values between 45 and 90 km in randomized order. The resulting score value represents the lowest range value which users still experience as perfectly comfortable (for further details, see Franke et al., 2011). Second, the 4-item threat scale of the primary appraisal secondary appraisal (PASA) questionnaire (Gaab, 2009) was used. This was framed for a situation where remaining range and remaining trip distance were equal. Third, the range safety buffer was assessed as the range level below which users were no longer willing to drive the EV. Users were asked to frame their responses to conditions of moderate daytime temperatures of 10–20 °C. Variables were inverted so that high values indicated high comfortable range. We derived the composite criterion for comfortable range from the three subscores using the first factor from principal-axis factor analysis (eigenvalue = 1.53, second factor = 0.84). The three subscores yielded acceptable factor loadings: range threat appraisal = .37, range game comfort zone = .73, range safety buffer = .47. The resulting factor score had one missing value and no outlier ($n = 39$).

2.6. Range satisfaction measure

At T_1 four items were used to assess users' range satisfaction, specifically whether the range: (1) suited their daily needs, (2) was a usage barrier, (3) met their expectations, and (4) resulted in the feeling of a limited action radius. Item values were reversed so that high values indicated high satisfaction. Cronbach's alpha was .75 ($n = 40$, no outliers or missing values).

3. Results

We analyzed our data using regression analyses. With the following exceptions the majority of assumptions were satisfactorily met (Stade et al., 2011). First, the internal consistency of range practice and competent range scores was unsatisfactory. Violating this assumption leads to an underestimation of R^2 and to a more conservative test of model fit (Stade et al., 2011). Such a result is not uncommon for scales combining only two subscores (Cortina, 1993). Moreover, internal consistency may underestimate reliability for heterogeneous measures of a construct (Yarkoni, 2010). Second, some cases were identified as outliers with residual z-values > |1.96|. Urban and Mayerl (2008) suggest to present results with and without these outliers. To aid readability, results after outlier exclusion are here only presented if their statistical significance or effect size magnitude differed importantly (e.g., change from a weak to a moderate effect). Third, available sample size was judged as sufficient for testing two predictors in one analysis assuming strong effects ($R^2 \geqslant .26$) and a desired statistical power of .80 (power calculation with G*Power; Faul et al., 2009).

The forced entry method was used for all analyses except the backward regression analysis in Subsection 3.5. As we had directional hypotheses for the effects of the individual predictors we tested one-tailed hypotheses except for omnibus tests of whole-model fit R^2 and for predictors in one exploratory analysis in Section 3.3.1. A significance level of .05 was used throughout. We tested the relationships of the predictor variables to every range level to examine if the range levels were indeed differentially related to the predictor variables as expected.

3.1. General range experience and range utilization

Based on the dichotomized 6-point scale, the majority of users (88%) agreed that the range offered by the EV was sufficient for everyday use, thus indicating high range satisfaction. Results also showed that stressful range situations occurred with only a mean frequency of 0.83 stressful events per month (SD = 1.28), and only 13% of users encountering more than one situation per month. The item asking participants to rate frequency of becoming nervous due to range received somewhat higher ratings, M = 1.13, SD = 1.24, 28% more than once per month.

Table 1 presents the score values for comfortable range variables. As the values of the upper and lower quartiles show, there were considerable inter-individual differences in comfortable range. In terms of average proportional range utilization, data from the range game suggested that users were comfortable utilizing 77% of available range resources, that is a 60-km trip distance with 78 km available range. A similar result was obtained when we related the comfortable trip distance value to the communicated range under daily conditions (71%, 120 of 168 km) or to the average value of the objective measure of performant range (77%, 120 of 156 km).

3.2. Personality traits and range levels

It is generally accepted that personality can be comprehensively described by five factors (Digman, 1990). Yet, to predict specific behavior and derive implications for interventions as well as to develop conceptual models, it has been suggested that one should focus on specific facets of the five factors (e.g. Paunonen and Ashton, 2001). We follow this suggestion but also aim to test whether the examined specific personality variables may relate to the same superordinate personality dimension and thus may share similar variance in range values. As sample size was only sufficient to test two predictors per analysis we grouped the personality variables based on their relatedness in a principal axis factor analysis (see Table 2). Although driving style is usually not treated as a personality trait, we included it in the analysis as we considered it a sufficiently stable personal characteristic. Three factors resulted according to both Kaiser-criterion and scree-plot, first factor eigenvalue = 1.83, second = 1.42, and third = 1.13. Each variable had a primary factor loading >.30 and all cross-loadings were <.30. The first factor was related to the two variables assumed to assess facets of individual driving style. The second factor referred to the personality traits related to enjoyment and self confidence in dealing with complex or demanding situations (control beliefs, need for cognition). The third factor comprised ambiguity tolerance and impulsivity. These two variables may be linked to a similar dimension of self-regulation style, in the context of dealing with new or uncertain situations.

Table 1
Descriptive statistics for comfortable range variables.

Variable	M	SD	Q_{25}	Q_{75}
Safety buffer	19.23	13.02	10.00	25.00
Range comfort zone	78.27	10.11	71.25	86.25
Range threat appraisal	3.33	1.07	2.50	4.00
Comfortable trip distance	120.41	16.93	100.00	130.00

Note: All variables are in km except for range threat appraisal (scale value on a 6-point scale).

Table 2
Factor loadings for principal axis factor analysis with varimax rotation of personality scales.

	Factor		
	1	2	3
Risk propensity in driving	**.84**	−.08	.02
Speedy driving style	**.79**	.14	.16
Control beliefs	−.05	**.58**	−.22
Need for cognition	.06	**.64**	.18
Ambiguity tolerance	.16	.29	**.36**
Impulsivity	.03	−.08	**.58**

Note: Factor loadings >.30 are in boldface.

As expected, the two predictors internal control beliefs and need for cognition accounted for some of the variance in comfortable and competent range (see Table 3). For comfortable range, there was a significant model fit, $R^2_{adj} = .13$, $F(2,32) = 3.59$, $p = .039$, that was stronger after outlier exclusion, $R^2_{adj} = .22$, $F(2,30) = 5.50$, $p = .009$. Yet, only control beliefs contributed significantly. The pattern was similar for competent range before, $R^2_{adj} = .16$, $F(2,28) = 3.84$, $p = .034$, and after outlier exclusion, $R^2_{adj} = .30$, $F(2,27) = 7.30$, $p = .003$. As expected, there was a moderate positive zero-order correlation for need for cognition. Yet, the part correlation of need for cognition was weak, indicating that need for cognition was redundant to control beliefs in predicting competent range. Explained variance for performant range was small (all $F < 1$).

Some of the variance was explained by the model including the predictors ambiguity tolerance and impulsivity for all range levels (see Table 4). For comfortable range, $R^2_{adj} = .12$, $F(2,35) = 3.60$, $p = .038$, was obtained. Ambiguity tolerance had a weak and non-significant effect that was in the opposite direction than expected. The effect of impulsivity was moderate, significant and in the expected direction. Competent range yielded a significant model fit only after outlier exclusion, $R^2_{adj} = .20$, $F(2,30) = 4.99$, $p = .013$ (before $R^2_{adj} = 12$, $F(2,31) = 3.26$, $p = .052$). For both predictors, ambiguity tolerance and impulsivity, moderate relations in the expected directions resulted, but only the effect of ambiguity tolerance was significant. Results revealed an unexpected model fit for performant range after outlier exclusion, $R^2_{adj} = .25$, $F(2,30) = 6.25$, $p = .005$ (before $R^2_{adj} = .10$, $F(2,31) = 2.76$, $p = .079$). It was driven by the moderate to strong positive relation of ambiguity tolerance to performant range.

For the two driving style variables the effect on performant range was weak before, $R^2_{adj} = .03$, $F(2,30) = 1.45$, $p = .250$, and after outlier exclusion, $R^2_{adj} = .07$, $F(2,28) = 2.18$, $p = .132$ (see Table 5). However, the indicator for speedy driving style yielded a moderate part correlation in the expected direction after outlier exclusion. Explained variance for comfortable range and competent range was small all $F < 1$).

3.3. System competence and range levels

In analyzing the role of subjective range competence and in all of the following univariate regression analyses, the *p*-value for the *F*-test statistic is also given one-tailed. As expected, there was a positive effect of subjective range competence on comfortable range, $R^2_{adj} = .09$, $F(1,35) = 4.48$, $p = .021$, that was even stronger after outlier exclusion, $R^2_{adj} = .13$, $F(1,33) = 6.09$, $p = .009$ (see Table 6). However, the expected effect on competent range was not found ($F < 1$). Explained variance for performant range was also small ($F < 1$). To examine this unexpected result further, we analyzed the two subscales of subjective competence (prediction versus control) as separate predictors (two-tailed exploratory tests, see Table 7). For competent range, a significant model fit resulted only after outlier exclusion, $R^2_{adj} = .20$, $F(2,28) = 4.80$, $p = .016$ (before $R^2_{adj} = .05$, $F(2,30) = 1.81$, $p = .181$). Control had a moderate negative effect and prediction a moderate positive effect. A similar pattern was obtained for performant range. Sizeable variance was explained before, $R^2_{adj} = .24$, $F(2,30) = 6.10$,

Table 3
Internal control beliefs and need for cognition as predictors of range level values.

	n		*B*		SE *B*		*p*		Part correlation		Zero-order correlation	
Comfortable range												
Control beliefs	35	(33)	0.49	(0.49)	0.20	(0.18)	.010	(.005)	.39	(.43)	.43	.50
Need for cognition	35	(33)	0.05	(0.15)	0.19	(0.17)	.396	(.195)	.04	(.14)	.18	.29
Performant range												
Control beliefs	31		0.10		0.24		.346		.08		.08	
Need for cognition	31		0.02		0.24		.471		.01		.03	
Competent range												
Control beliefs	31	30	0.49	0.57	0.21	0.18	.014	(.002)	.39	(.48)	.45	.57
Need for cognition	31	30	0.12	0.18	0.19	0.17	.271	(.136)	.10	(.17)	.25	.34

Note: Results after outlier exclusion are given in parentheses; *p*-values are one-tailed.

Table 4
Ambiguity tolerance and impulsivity as predictors of range level values.

	n		*B*		SE *B*		*p*		Part correlation		Zero-order correlation	
Comfortable range												
Ambiguity tolerance	38		−0.16		0.19		.199		−.13		−.19	
Impulsivity	38		−0.15		0.06		.011		−.37		−.39	
Performant range												
Ambiguity tolerance	34	(33)	0.48	(0.64)	0.21	(0.18)	.013	(.001)	.39	(.54)	.38	(.54)
Impulsivity	34		−0.04		0.07		.299		−.09		−.02	
Competent range												
Ambiguity tolerance	34	(33)	0.39	(0.52)	0.20	(0.19)	.029	(.004)	.32	(.44)	.26	(.40)
Impulsivity	34		−0.12		0.06		.027		−.33		−.27	

Note: Results after outlier exclusion are given in parentheses; *p*-values are one-tailed.

Table 5
Speedy driving style and risk propensity in driving as predictors of range level values.

	n		*B*		SE *B*		*p*		Part correlation		Zero-order correlation	
Comfortable range												
Speedy driving style	37		0.12		0.17		.240		.12		.11	
Risk propensity in driving	37		−0.03		0.08		.362		−.06		.02	
Performant range												
Speedy driving style	33	(31)	−0.25	(−0.29)	0.18	(0.16)	.087	(.041)	−.24	(−.32)	−.30	(−.37)
Risk propensity in driving	33		−0.00		0.09		.496		−.00		−.17	
Competent range												
Speedy driving style	33		−0.15		0.16		.179		−.17		−.24	
Risk propensity in driving	33		−0.03		0.08		.345		−.07		−.19	

Note: Results after outlier exclusion are given in parentheses; *p*-values are one-tailed.

Table 6
Subjective range competence as predictors of range level values.

	n		*B*		SE *B*		*p*		Zero-order correlation	
Comfortable range										
Subjective range competence	37	(35)	0.47	(0.48)	0.22	(0.20)	.021	(.009)	.34	(.40)
Performant range										
Subjective range competence	33		−0.09		0.24		.348		−.07	
Competent range										
Subjective range competence	33		0.08		0.22		.355		.07	

Note: Results after outlier exclusion are given in parentheses; *p*-values are one-tailed.

Table 7
Subjective competence in predicting and controlling range as predictors of range level values.

	n		*B*		SE *B*		*p*		Part correlation		Zero-order correlation	
Comfortable range												
Control	36		0.38		0.21		.085		.29		.33	
Prediction	36		−0.08		0.33		.805		−.04		.16	
Performant range												
Control	33	(32)	−0.61	(−0.72)	0.19	(0.17)	.004	(<.001)	−.49	(−.61)	−.25	(−.35)
Prediction	33	(32)	0.95	(1.00)	0.30	(0.26)	.004	(.001)	.48	(.55)	.23	(.22)
Competent range												
Control	33	(31)	−0.27	(−0.42)	0.20	(0.16)	.181	(.015)	−.24	(−.42)	−.05	(−.16)
Prediction	33	(31)	0.58	(0.74)	0.31	(0.25)	.069	(.006)	.32	(.48)	.23	(.28)

Note: Results after outlier exclusion are given in parentheses; *p*-values are two-tailed.

Table 8
Prior knowledge as predictor of range level values.

	n		*B*		SE *B*		*p*		Zero-order correlation	
Comfortable range										
EV technology knowledge	38		0.14		0.11		.117		.20	
Performant range										
EV technology knowledge	35		0.08		0.12		.262		.11	
Competent range										
EV technology knowledge	35	(34)	0.18	(0.18)	0.11	(0.10)	.052	(.040)	.28	(.30)

Note: Results after outlier exclusion are given in parentheses; *p*-values are one-tailed.

$p = .006$, and even more after outlier exclusion, $R^2_{adj} = .38$, $F(2,29) = 10.61$, $p < .001$. Control had a strong negative effect and prediction had a strong positive effect. For comfortable range, model fit was not significant, $R^2_{adj} = .06$, $F(2,33) = 2.03$, $p = .148$. Only control had a moderate positive effect and prediction had no effect.

For prior knowledge, there was a significant effect on competent range as expected but only after outlier exclusion, $R^2_{adj} = .06$, $F(1,32) = 3.27$, $p = .040$ (before $R^2_{adj} = .05$, $F(1,33) = 2.81$, $p = .052$) (see Table 8). Only weak effects for comfortable and performant range were found ($F < 1.5$).

Table 9
Daily practice as a predictor of range level values.

	n		B		SE B		p		Zero-order correlation	
Comfortable range										
Range practice	32	(30)	0.11	(0.28)	0.18	(0.14)	.272	(.030)	.11	(.35)
Performant range										
Range practice	27		0.18		0.19		.187		.18	
Competent range										
Range practice	27		0.32		0.16		.027		.38	

Note: Results after outlier exclusion are given in parentheses; p-values are one-tailed.

Table 10
Performant and competent range as predictors of comfortable range.

	n	B	SE B	p	Part correlation	Zero-order correlation
Performant range	33	−0.84	0.23	<.001	−.56	−.39
Competent range	33	0.71	0.26	.006	.41	−.01

Note: p-Values are one-tailed.

Table 11
Comfortable range as predictor of range satisfaction.

	n		B		SE B		p		Zero-order correlation	
Comfortable range	39	(38)	0.30	(0.35)	0.18	(0.17)	.049	(.022)	.27	(.33)

Note: Results after outlier exclusion are given in parentheses; p-values are one-tailed.

There was a moderate effect of daily range practice in the expected direction for competent range, $R^2_{adj} = .11$, $F(1,25) = 4.11$, $p = .027$, and comfortable range after outlier exclusion, $R^2_{adj} = .09$, $F(1,28) = 3.84$, $p = .030$ (before, $F < 1$) (see Table 9). The effect for performant range was weak ($F < 1$).

Performant and competent range levels predicted substantial variance in comfortable range, $R^2_{adj} = .27$, $F(2,30) = 6.94$, $p = .003$; no outlier(see Table 10). Competent range yielded a moderate positive effect as expected. Performant range had a strong negative effect. This last effect was counter to what we expected.

3.4. Relation of range levels to range satisfaction

A backward regression analysis was conducted to identify the range levels that could explain variance in range satisfaction. Model fit with all three range levels was very weak and not significant ($F < 1$). Excluding the variable that explained the least variance (performant range) also did not result in a significant model fit, although explained variance increased, $R^2_{adj} = .03$, $F(2,32) = 1.59$, $p = .219$. Only the model with comfortable range could reliably explain variance in range satisfaction, and a moderate effect in the expected direction was obtained before, $R^2_{adj} = .05$, $F(1,37) = 2.86$, $p = .049$, and after outlier exclusion, $R^2_{adj} = .08$, $F(1,36) = 4.40$, $p = .022$ (see Table 11).

4. Discussion

The present research investigated the psychological dynamics of user–range interaction from a self-regulation perspective. In accordance with our previous study (Franke et al., 2011), range satisfaction of users with 3 months of EV experience was high, and situations where users felt stressed or nervous due to range seldom occurred. Comfortable range indicators suggested that the average user was comfortable utilizing 75–80% of available range resources.

Most hypotheses derived from our conceptual model were supported. First, there was indeed substantial variation in range level values supporting the proposed complexity of user–range interaction. Second, regarding personality traits, control beliefs and low impulsivity were positively linked to comfortable and competent range, ambiguity tolerance was positively linked to competent range whereas the link to comfortable range was not obtained. Need for cognition was related to competent range, but the observed correlation with control beliefs make conclusions uncertain. None of these variables, except for ambiguity tolerance, was linked to performant range, supporting our notion of distinct range levels. Likewise, speedy driving style was only negatively related to performant range. Yet, there was no link of risk propensity in driving to performant range. Third, regarding system competence variables (i.e., coping skills), daily practice was positively related to comfortable and competent range and prior knowledge to competent range. Again, performant range was not affected by these variables. The relationship of subjective range competence to range level values was more complicated than hypothesized. While the link to comfortable range was as expected, only the subscale "prediction" was positively related to competent range while the subscale "control" showed a negative relationship. Unexpectedly, there was a similar pattern for performant range. Fourth, regarding relationships among range levels, comfortable range was indeed partly explained by performant and competent range. Both predictors seemed to play different roles in this relationship. In the following, we first discuss the implication of the results for refining the model and for practical applications, then we discuss some limitations and needs for additional research.

The positive relationship of competent range to comfortable range implies that improvement of maximum performance may also lead to expansion of the range comfort zone. Conversely, a decrease in range safety buffers may lead to more ambitious trip planning, more experienced critical range situations with higher situational range awareness, and finally to better range management skills. This in turn could enhance competent range. Future research should clarify these possible causal chains for refining the conceptual model. In terms of practical implications, the relationships between the range levels indicate the potential of user information and training for extending the practically usable range. Notably, there was no zero-order correlation between comfortable and competent range. Only when performant range was partialled out, a moderate part correlation resulted. This means that essentially the gap between performant and competent range determines the range comfort zone.

Counter to our hypotheses, performant range was negatively associated with comfortable range. Perhaps a higher performant range reduces the need to expand the range comfort zone. Conversely, a higher comfortable range could make users reduce their efforts to optimize (increase) their available range in everyday driving. A tentative conclusion is that there are two ways to adapt to the limited range of an EV and safeguard a comfortable user experience. Either users expand their comfort zone (i.e., reduce range buffers), which will lead to a higher mileage traveled at lower remaining range values, or they improve average range performance and thus travel with higher values of remaining range (e.g., higher range buffers but larger absolute available range). In other words, users can maintain a level of desired risk or task difficulty by following one of these two strategies. Conceptions of task difficulty and risk homeostasis are well documented (Fuller, 2005) and fit into the control framework, which we posit is the basis for user–range interaction. For optimal range utilization it would be desirable to "break through" this homeostatic mechanism so that EV users strive for both increasing their range comfort zone and increasing their available range resources.

A powerful predictor for range utilization appears to be low internal control beliefs in dealing with technology. The second-best predictor seems to be high impulsivity. For the latter, it is especially noteworthy that it was obtained with a single-item measure. Such short scales would be useful for a practical screening tool. However, the effect of impulsivity needs further replication. For ambiguity tolerance, the positive effect on comfortable range found in our previous study (Franke et al., 2011) was not replicated. We have no explanation for this especially given the clear link of ambiguity tolerance to stress resistance generally found in the literature (e.g., Frone, 1990). However, there was a moderate positive association to competent range and, unexpectedly, to performant range. Ambiguity tolerance seems to facilitate average and maximum performance. We tentatively conclude that different styles of adapting to EV range may account for the differential effects for comfortable, performant, and competent range. Need for cognition seems to be redundant to internal control beliefs in accounting for variance in competent range given only a moderate zero-order and no part correlation. As expected, personality attributes related to driving style were only linked to performant range. However, this effect was weak and only driven by a moderate negative correlation of speedy driving style to performant range. Future research should aim for a more comprehensive assessment of driving style incorporating attitudes and personal values.

Regarding system competence variables we found all but one of the expected effects. First, prior knowledge was positively related to competent range. Consequently, users should be provided with sufficient background knowledge when purchasing an EV for ensuring successful self-regulated learning. Second, a positive effect of daily practice on comfortable range and competent range was obtained. Thus, actively promoting regular EV driving practice via user instructions and feedback may help users expand their range comfort zone and achieve maximum performance. Third, the effect of subjective competence was only present for comfortable range. Further explorations at the subscale level (predicting vs. controlling range) revealed that this was due to a negative relation of subjective range control competence and at the same time, a positive relation of subjective range prediction competence to competent range. We do not have an explanation for this. It could be that users with a strong belief in their range control abilities simply do not regard increasing their available range necessary because they are comfortable with lower remaining range situations. The similar pattern of results for performant and competent range supports this notion. Perhaps an illusion of control is beneficial for reaching a high level of comfortable range but not of competent range. This is further supported by the relation of range competence to comfortable range, which is mostly driven by the positive effect of subjective range control competency. Reaching a high level of maximum performance (e.g., competent range) may go hand in hand with obtaining a more balanced view of the controllability of range, which in turn produces a negative relation to subjective range control competency. This interpretation remains speculative and requires further empirical testing.

One question remains. Why is there a positive effect of trait control beliefs on competent range when there is a negative effect of more situation-specific subjective competence in controlling range? Research on the related concept of self-efficacy has also found general (trait) self-efficacy to be positively related to performance whereas more task-specific self-efficacy is negatively related to performance (e.g., Yeo and Neal, 2006). Trait control beliefs should more generally affect persistence and goal pursuit, whereas situational control beliefs can lead to decreased resource allocation to the task, thus preventing performance improvement (Vancouver and Kendall, 2006; Yeo and Neal, 2006).

Regarding the link of range levels to range satisfaction, only comfortable range accounted for considerable variance in range satisfaction scores. This reinforces that comfortable range is the most important determinant of range utilization. Although this effect is not very strong, it is noteworthy in terms of practical significance, especially if one considers that there are more proximate factors for range satisfaction, such as users' objective mobility needs or the share of mobility needs that users aim to assign to the EV. Comfortable range may account for a relatively small share of variance in range satisfaction, but this could represent the predominant one for inducing change.

Summarizing the discussion above, the results support our conceptual model. It thus seems fruitful to apply self-regulation and control theory and to distinguish three range levels to explain user–range interaction. The predictor variables were differentially linked to these different range level variables mostly in line with our hypotheses. However, further research is needed to better understand the relationships and interactions of range levels and range-related behavior. Also, easier-to-assess and less complex measures of range level values would render them more accessible in future research.

There are some limitations of the present study. Given the field trial design, inferences about causal relationships cannot be drawn. The causal chains of the conceptual model should therefore be examined in future studies. Moreover, significant effects may have not been discovered due to the small sample size, partly low reliability of measures (e.g., performant and competent range measures), restriction of variance on some variables (e.g., personality), and the fact that experienced critical range situations were seldom encountered.

Furthermore, users had access to at least one additional conventional car besides the EV. This option may have caused less range stress and higher range satisfaction as well as different ways in adapting to EV range (e.g., less need to acquire a high competent range). Although such hybrid households may be common in the EV market (Kurani et al., 1996) future research should also examine user–range interaction in settings were the EV is the only car available to users.

Our results are based on a sample of early adopters of EVs. Early adopters accept more usage barriers than the average customer (Rodriguez and Page, 2004), for instance, a two-seater layout and minimal trunk space as in the present case. Time to adoption is related to certain personality characteristics (Rogers, 2003). Hence, an early adopter sample will be restricted in variance on personality variables, as we observed in our data (e.g., our users only scored in the upper half of possible scale values for internal control beliefs). Hence, the personality effects in this study likely underestimate the effect in the whole population of car buyers. In conclusion, although a finding of 75–80% average comfortable range utilization seems high, this may represent the upper limit of unsupported range utilization because early adopters are highly motivated and skilled and show favorable personality characteristics. Nevertheless, we believe that understanding this target group is important as it represents the wellspring for EV market penetration. Still, further research with mainstream drivers is needed, where more critical EV attitudes and less favorable interaction patterns are likely (Graham-Rowe et al., 2012). The same holds true for groups with more sporadic usage, such as car-sharing and company fleet settings, where, for example, intrinsic motivation for adapting to an EV might be lower (Burgess and Harris, 2011).

Finally, for accurate market predictions and policy decisions it is also critical to understand the nature of societal adaptation to EVs. Ideally, people may come to view EVs not as short-range combustion vehicles but as a new, distinct mode of transportation. Such adaptation would likely be best supported by EV concepts that shift from combustion conversions to vehicles that are innately electric.

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Field study

ABSTRACT

We examined the psychological dynamics underlying charging behaviour of electric vehicle (EV) users. Data from 79 EV users were assessed in a 6-month EV field study. On average, users charged their EV three times per week, drove 38 km per day, and they typically had a large surplus of energy remaining upon recharging. Based on first findings concerning charging style among mobile phone users, we hypothesized that user–battery interaction style (UBIS) is a relevant variable for understanding charging behaviour of EV users. We developed measures to assess UBIS. Results show that it is a relatively temporally stable characteristic which also shows some cross-device consistency. As predicted by our conceptual model, UBIS and comfortable range explain the charge level at which people typically recharged. UBIS was related to users' confidence in their mental model of range dynamics, the utilization of range, and to excess energy from renewable sources. This research has implications for optimizing sustainability of electric mobility systems.

1. Introduction

EVs are a promising form of sustainable[1] transportation because of their potential to reduce CO_2 emissions and air pollution (Holdway, Williams, Inderwildi, & King, 2010), mitigate risks associated with peak oil (Hirsch, Bezdek, & Wendling, 2005), and utilize excess energy from renewable sources like wind (Sundström & Binding, 2010). However, these effects are dependent on how an electric mobility system (EMS) is set up as well as how it is used (Eggers & Eggers, 2011; Franke, Bühler, Cocron, Neumann, & Krems, 2012). Therefore, the user is a critical parameter in the equation specifying the net environmental and economic benefit of an EMS.

Research has shown that it is challenging for users to utilize an EMS in an optimal way. For example, regarding the efficient use of limited energy resources, users have been found to maintain substantial psychological safety buffers in their range utilization (Caroll, 2010; Franke & Krems, 2013; Franke, Neumann, Bühler, Cocron, & Krems, 2012). This inefficient utilization of precious range resources has an adverse impact on the ecological and economic sustainability of EMS, because battery size is linked to ecological footprint (Hawkins, Gausen, & Strømman, 2012; McManus, 2012) and the affordability (i.e., chance for broad adoption) of EVs (Neubauer, Brooker, & Wood, 2012; Thomas, 2009). Thus, it would be beneficial to avoid wasting substantial shares of usable battery capacity as psychological safety buffer, but how can EV users be supported in the efficient utilization of energy resources?

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[1] With the term sustainability we refer to the "three pillars" model of sustainable development (UN General Assembly, 2005) covering environmental, economic and social facets of sustainability. In particular, EVs must be beneficial for environmental protection and economic development to be considered a sustainable technology. This especially refers to the efficient use of energy and resources.

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Findings show that some users adopt more efficient usage patterns than others and certain psychological variables have been found to be related to those individual differences (Franke & Krems, 2013; Franke, Bühler, et al., 2012; Franke, Neumann, et al., 2012). These variables may help to inform the development of strategies promoting more sustainable utilization of an EMS. It is therefore important to understand variables underlying individual differences in EMS users' utilization of energy resources, both, in terms of depletion (e.g., trip decisions) and replenishment (e.g., charging decisions) of resources. Previous research in this area has largely focused on the former facet, depletion of resources (Franke & Krems, 2013; Franke, Neumann, et al., 2012). The present research aims to better understand the psychological dynamics underlying replenishment of resources (i.e., charging decisions).

To this end, a field trial approach was applied in which 79 participants leased an EV for 6 months and provided subjective and objective data. In order to advance the adaptive control of range resources framework (Franke & Krems, 2013; Franke, Neumann, et al., 2012), we applied concepts developed through preliminary research on mobile phone users charging style (Rahmati & Zhong, 2009) to the field of electric mobility. We developed measures to assess participants' charging-related user–battery interaction style (UBIS) and analyzed characteristics of UBIS, accordingly. We then examined if UBIS is associated with certain charging patterns. In addition, we examined whether UBIS and comfortable range can account for variance in charging behaviour, and whether there is an association between UBIS and users' confidence in their mental model of range dynamics. Finally, we analyzed the relationship between UBIS and efficient usage of the EMS, with a focus on range utilization and the efficiency of utilizing excess energy from wind.

1.1. Interacting with limited energy resources

To better understand the efficient use of energy (i.e., mobility) resources, we have developed a conceptual model (Franke & Krems, 2013; Franke, Neumann, et al., 2012), based on principles of self-regulation and control theory (Carver & Scheier, 1998; Fuller, 2011). Our model is similar to the transactional model of stress (Lazarus & Folkman, 1984) in that it proposes a highly subjective appraisal of range resources and a high variance in coping strategies. Indeed, in previous research, we found substantial variance in users' appraisal of objectively similar range resource situations (Franke & Krems, 2013; Franke, Neumann, et al., 2012) and identified several stress-buffering variables similar to those Lazarus and Folkman (1984) proposed (e.g., internal control beliefs). Rather than focusing on users' individual *appraisal* of available range resources, the present study focuses on individual differences in *coping style* related to charging. Fig. 1 depicts the model from the perspective of a single charging decision (i.e., the control loop of user–battery interaction).

The model is based on the premise that whenever users interact with limited energy resources, they continuously monitor and manage the relation between their mobility needs (e.g., distance of next trip) and their mobility resources (e.g., remaining range). This ratio (i.e., the perceived available range buffer) is then compared to the user's preferred range buffer (i.e., the user's comfortable range) which has been shown to vary considerably between users (Franke & Krems, 2013; Franke, Neumann, et al., 2012). The range appraisal (the experienced discrepancy between available and preferred range resource buffers) leads to a certain degree of range stress (i.e., range anxiety). The more range stress, the more likely the user will apply coping strategies (e.g., drive more economically, charge the car) to resolve the situation. Consequently, the users' comfortable range plays a key role in predicting the likelihood that a user will apply coping strategies (e.g., charging) in a given situation.

Although appraisal of a range situation is an important determinant of users' coping behaviour, we do not assume that this is the only determining factor; rather, we posit that users adopt a preferred coping style when dealing with limited energy resources which we call user–battery interaction style (UBIS). This is based on the observation, that although EV energy resources are limited, experience of subjectively critical range situations is still relatively infrequent (Franke & Krems, 2013;

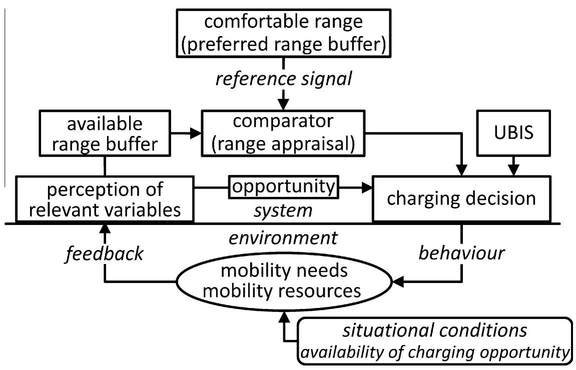

Fig. 1. A charging decision according to the adaptive control of range resources model (i.e., the control loop of UBI). The likelihood of charging increases as the salience of a critical remaining range situation increases (available ⩽ comfortable range). Users with a lower UBIS will, however, tend to avoid such situations by charging more often than necessary and therefore, they will tend to base their decision on contextual triggers (i.e., the opportunity to charge). In contrast, users with a higher UBIS will tend to base their decision on range resources (i.e., the experienced necessity to charge). Hence, comfortable range affects the control process at an earlier stage (appraisal) while UBIS affects the control process at a later stage (decision on coping behaviour).

Franke, Neumann, et al., 2012); therefore, EV users seem to be mostly free to choose how they manage their battery resources in everyday use. In this respect, interacting with EV energy resources is similar to driving a car which is also commonly seen as a ''self-paced'' task (Elander, West, & French, 1993; Lajunen & Özkan, 2011), that allows individuals to adopt a preferred driving style (Lajunen & Özkan, 2011). Therefore, similar to the common notion driving style we hypothesize that users also adopt a certain coping style to interact with limited battery resources (e.g., EV charging style).

1.2. Individual differences in charging style

Most previous research on charging of pure EVs has focused on qualitative descriptions of charging behaviour (see e.g. Caroll, 2010). However, in the field of mobile phones, Rahmati and Zhong (2009) conducted a study with the specific aim of understanding the variables underlying charging behaviour. These researchers have proposed the term ''human–battery interaction'' (although we prefer user–battery interaction, UBI) to refer to the reciprocal process by which users manage the limited energy resources stored in the battery (Rahmati, Qian, & Zhong, 2007; Rahmati & Zhong, 2009). The term battery in UBI is used in a rather broad sense, referring to the whole energy supply system, including the user interface for controlling and regulating in- and outflow of energy (i.e., energy status displays, power controls, charging interface). Because the objective of the present study is to advance understanding of charging behaviour, we focus solely on the charging-related facet of UBI in the remaining sections.

Based on two small-scale field studies (10 participants over 4 weeks; 14 participants over 4 months) incorporating qualitative interviews and tracking of charging behaviour, Rahmati and Zhong (2009) suggested a classification of users into two user–battery interaction types: Type-a users who are characterized by a low UBI (i.e., unintensive interaction with battery resources) and Type-b users who are characterized by a high UBI (i.e. intensive interaction with battery resources). The typological terminology likely arose from the specific methodology (e.g., qualitative analysis of charging behaviour and subjective data) used in this studies. Herein, low-UBI type was proposed to be marked by flatter (i.e. evenly and broadly distributed) histograms of charge level at start of charge, whereas high-UBI type was visibly indicated by histograms that had a clear peak. In contrast to this typological view, yet consistent with the more common conceptualization of driving style (Elander et al., 1993), we posit that UBI should be conceptualized as a continuum from low to high intensity of interaction with battery resources. We use the term UBI style (UBIS) to better represent our conceptualization. The factors that we expect to predict the development of a certain UBIS as well as the variables that are presumable affected by UBIS are depicted in Fig. 2.

Similar to Rahmati and Zhong (2009), we hypothesize that high versus low UBIS is the expression of different general resource optimization strategies: while users with a lower UBIS try to reduce their continuous cognitive and perceptual load associated with energy-resource management, users with a higher UBIS try to reduce their motor and partly cognitive load for charging more often than necessary. Consequently, we expect that UBIS has structural similarities to other behavioural or activity-centred styles (e.g., driving style; Kleisen, 2011) as well as to cognitive styles (Zhang & Sternberg, 2005).

This preferred strategy presumably causes users with a lower UBIS to charge their devices regularly based on contextual triggers regardless of charge level (e.g., whenever possible, every evening), while users with a higher UBIS only charge when their subjectively preferred charge level is reached. Thus, it is expected that users with a lower UBIS likely have less awareness of their devices' energy level and consequently develop less precise mental models of battery-level dynamics and their power impact than users with a higher UBIS. A precise mental model of range dynamics supports a generally effective and adaptive interaction with energy resources. Therefore, consistent with Rahmati and Zhong (2009), we hypothesize that users with a lower UBIS will be less likely to take full advantage of available battery resources (i.e. show reduced range utilization). The notion that increased awareness of elements in the environment (i.e., situation awareness) is related to better situation models, and therefore, in the long run, also to better mental models, is common in other areas of human factors research (Endsley, 2000). A mental model in this sense is an internal representation of a physical system that can be used, for example, to derive predictions of system states (Endsley, 2000).

Moreover, UBIS will not only be driven by the personally preferred strategy of interacting with battery resources, but also by characteristics of both the device and the environment. The higher the battery life of a device is in relation to the

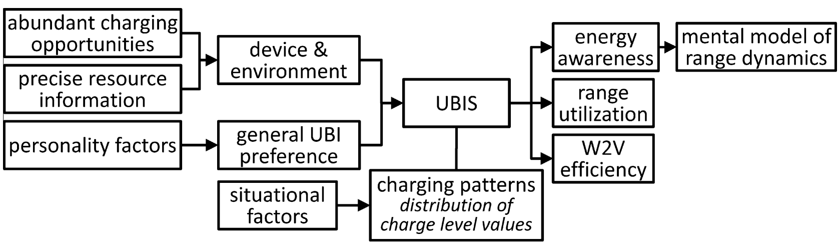

Fig. 2. Variables hypothesized to predict the development of a certain UBIS and variables affected by UBIS. The general UBI preference acts as an anchor for the UBIS that users adopt. UBIS is also influenced by characteristics of the device and the environment which limit users' flexibility in interacting with energy resources. UBIS is a variable on the decision level. It should be visible in behavioural patterns which are however also driven by situational factors (i.e., environmental noise). A high UBIS (i.e., more intensive interaction with battery resources) should lead to (1) more energy awareness and therefore more precise mental models of range dynamics and (2) a higher utilization of range resources but (3) also to a lower wind-to-vehicle (W2V) efficiency (see Sections 1.3 and 2.3.7).

frequency of encountering charging opportunities (i.e., abundant charging opportunities), the more likely users will adopt a higher UBIS. For instance, adoption of a higher UBIS is more likely in mobile phone use than in laptop use (Banerjee, Rahmati, Corner, Rollins, & Zhong, 2007) and users who lose charging opportunities due to lifestyle changes can change to a lower UBIS (Rahmati & Zhong, 2009). Additionally, a precise and informative charge level indicator is critical for the adoption of a higher UBIS (Rahmati & Zhong, 2009). Related work in the field of refuelling behaviour (Sperling & Kitamura, 1986) has also tentatively proposed that car drivers could be classified into two groups similar to UBIS: (a) people who largely base their refuelling decisions on perceived necessity to refuel and (b) people who focus on external triggers, apart from fuel level (e.g., service, convenient location of refuelling station). Again, people operating in a network with a lower density of refuelling opportunities were less likely to refuel when fuel was running low than individuals operating their vehicles under conditions with more abundant refuelling opportunities.

In sum, after users have adapted to a specific configuration of device and environment demands, we expect UBIS to be relatively temporally stable. Because UBIS is presumed to be an expression of a general UBI preference (see Fig. 2), it is also expected to show some cross-device (i.e., cross-situational) consistency. These two propositions are supported by theory and findings in related fields: First, driving style has also been found to be relatively temporally stable (Lajunen & Özkan, 2011) and partly attributable to more general personality traits (Elander et al., 1993; Taubman-Ben-Ari, Mikulincer, & Gillath, 2004). Second, in the extensive literature on intellectual styles (i.e., thinking or cognitive styles; Zhang, Sternberg, & Rayner, 2012), which have also been linked to driving style (Kleisen, 2011), styles are also commonly considered to be relatively temporally stable (Kozhevnikov, 2007; Zhang et al., 2012). Moreover, cognitive styles have been conceptualized as having a hierarchical structure (Kozhevnikov, 2007; Zhang et al., 2012). Hence, there are rather general (i.e., superordinate) styles and rather specific (i.e., subordinate) styles. The more general styles have also been assumed to be more stable than the more specific styles (Curry, 1983). Finally, styles are at least in part a function of general personality traits (Curry, 1983; Kozhevnikov, 2007).

Regarding sustainable interaction with EMS, a higher UBIS is presumed to be beneficial because it is presumably related to a more efficient utilization of limited range resources. Users with a higher UBIS more actively interact with battery resources and may more often exhaust the available range, which has been shown to improve their learning process in dealing with EV range (Franke, Cocron, Bühler, Neumann, & Krems, 2012; Franke & Krems, 2013; Franke, Neumann, et al., 2012). Yet, under conditions where a more frequent connection to the power grid would be beneficial (i.e., wind to vehicle charging, see Sections 1.3 and 2.3.7), a low UBIS would be preferable from a sustainability perspective.

1.3. Study objectives

The purpose of the present study is to advance understanding of the psychological dynamics underlying charging behaviour and to determine the applicability of the UBIS concept in this regard. Moreover, we aim to examine the relation of UBIS to sustainable behaviour in managing energy resources in an EMS. To this end, the present study provides the first quantitative examination of the characteristics of UBIS and its relationships to other relevant variables.

First, the following research questions were addressed in exploratory analyses: (Q1) How do EV users experience charging? (Q2) How do users charge their EVs under everyday conditions? (Q3) Is UBIS a temporally stable, and cross-device (i.e., cross-situational) consistent characteristic?

Second, the following hypotheses were tested: (H1) Previous research suggests that UBIS can be observed by examining the distribution of charge level at start of charge (Rahmati & Zhong, 2009). In particular, charge level at start of charge should be more equally (i.e., broader) distributed for users with a lower UBIS while it should be more normally (i.e., distinct peak, narrower) distributed users with a higher UBIS. This is a test of criterion validity of the UBIS scale. (H2) This is the main test of our conceptual model in Fig. 1. Comfortable range (i.e., user's preferred range buffer) and UBIS (i.e., the tendency of whether a user orients to this level or not), together should explain when people charge their EV. Specifically, our model predicts that the higher users score on these two variables, the lower the charge level at which they typically recharge. (H3) Given their more intense interaction with the energy supply system, we expect users with a higher UBIS to develop more precise mental models of battery-level dynamics and of their power impact. Consequently, we hypothesize that users with a higher UBIS will give estimates of the impact that certain conditions have on range with higher confidence. (H4) Consistent with the proposal of Rahmati and Zhong (2009), we hypothesize that users with a higher UBIS will better exploit full battery capacity, in terms of range utilization. (H5) A major advantage of EVs is that they can use excess energy from renewable sources (e.g., wind) when controlled charging algorithms are applied (Westermann, Kratz, Ifland, & Schlegel, 2010) such as in the present field trial. As a frequent connection to the grid is beneficial for utilizing excess energy (see Section 2.3.7), we hypothesize that the higher the UBIS, the lower wind-to-vehicle efficiency.

2. Method

2.1. Field study setup

The present research was part of a large-scale EV field trial in the metropolitan area of Berlin, Germany, set up by the BMW Group and Vattenfall Europe, and funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. It was part of an international EV field trial (Vilimek, Keinath, & Schwalm, 2012). The EV was a converted MINI Cooper with a 168-km range under normal driving conditions and 250 km under ideal conditions (miniusa.com, 2012). It was equipped with both state-of-charge and remaining-range displays (km). A charge level warning was first displayed briefly at 30% state of charge (SOC) and then constantly below 16 km remaining range (around 10% SOC). The EV had regenerative braking to recover energy during deceleration. Test drivers had access to a network of 50 public charging stations in the metropolitan area of Berlin, as well as a private home-based charging station (4 h full charge duration at 32 A). The field trial consisted of two consecutive 6-month user studies (S1 and S2) with the same methodology and 40 participants each. For each user, data were collected prior to receiving the EV (T0), after 3 months of driving (T1), and upon returning the EV after 6 months (T2). At each point of measurement, users filled out 1-week travel and charging diaries (T1, T2), and completed a 2- to 3-h face-to-face interview including questionnaires. Logger data were recorded by the BMW Group and were related to subjective data through personalized keys. Additional details on the field trial methodology are reported in other publications (Cocron et al., 2011; Franke, Bühler, et al., 2012).

2.2. Participants

Eighty participants were selected from more than 1000 applicants recruited via an online screening instrument that was announced in both print and online media. Requirements for participation in the study were residence in the Berlin metropolitan area, willingness to pay a monthly leasing rate of 400 Euros, to take part in interviews, and to install a private home-based charging box. Additional criteria aimed to increase variance in basic socio-demographic (e.g., age, gender, education) and mobility-related variables (e.g., mileage, vehicle fleet). Despite these efforts our sample was still restricted in variance on basic socio-demographic characteristics compared to the general population of car drivers. The sample can rather be assumed to represent early adopters of EVs in German metropolitan areas. Data collection focused on the main EV user in the household. The 79 users who completed T1 had a mean age of 49 years (SD = 9.57), 67 were male, and 59 had a university degree.

2.3. Scales and measures

All questionnaire items used a 6-point Likert scale from (1) *completely disagree* to (6) *completely agree,* unless otherwise stated. The measures used in the present study are described below in the order of their appearance in the Results section.

2.3.1. Travel and charging diaries

The travel diary was a person-based record of all trips taking place in 1 week (e.g., mode of transport, distance, time, purpose). The average daily distance driven with the EV in a typical week was derived from the T1 travel diary. Data for the 5 workdays (Monday to Friday) were used because users reported that weekend trips were atypical and there were several missing values for weekend days. Complete data were available for n = 68 users.

The charging diary was a car-based record of all charging events in 1 week (e.g., charge level in terms of SOC and remaining range, time, location). As the main user of the EV was defined as the unit of analysis for all the analyses, charging events initiated by other users were excluded from the data set. For each main user (1) the number of charging events and (2) the average charge level at start of charge (CLstart) were derived from the T1 charging diary. Data were available for n = 70 participants. CLstart values were assessed both in terms of SOC and remaining range, as users could use both indicators to estimate their remaining energy resources. As these score variants were highly correlated (r = .95), we combined them with a factor score (CLstartM_CD) for use in regression analysis (n = 69 because of missing values in remaining range variable of one user).

2.3.2. UBIS scales

We developed two scales to assess UBIS: UBIS-8 and UBIS-1. Both were administered at T2 in S1 and S2. In addition, UBIS-1 was also administered at T1 in S2. UBIS-8 consisted of four items indicative of a high UBIS (e.g., "I typically charged when the state of charge fell to a certain level") and four items of a low UBIS (e.g., ". . . a particular timeframe had elapsed ..."). The latter four items (item IDs l1–l4) were reverse scored so that for all 8 item variables, high numbers indicated high UBIS (for full item texts and item IDs see Appendix A). Data were available for n = 75 users. To examine the dimensional structure of the variable set, we conducted a factor analysis using the program FACTOR (Lorenzo-Seva & Ferrando, 2006). Three cases had identical extreme values on two item variables (z = −2.74 resp. −2.97). Factor analysis results can be significantly distorted by outliers (Liu, Zumbo, & Wu, 2012). When extracting one factor based on our theoretical expectations using unweighted least squares extraction, factor loadings were partly unsatisfactory (h1 = .68, h2 = .87, h3 = .44, h4 = .83, l1 = .15, l2 = .15, l3 = .20, l4 = .37). Yet, without the three cases mentioned above (n = 72), factor loadings were all satisfactory (h1 = .57, h2 = .74, h3 = .37, h4 = .69, l1 = .37, l2 = .45, l3 = .34, l4 = .52). Parallel analysis (Timmerman & Lorenzo-Seva, 2011), however, indicated that two factors best accounted for the data when n = 75. Given n = 72, both a two factor and a single factor (according to more stringent 95th percentile criterion; Glorfeld, 1995) solution were indicated. In both samples, extracting two factors (promin rotation; Lorenzo-Seva & Ferrando, 2006) led to a clear pattern: items indicative of a high UBIS (h1–h4) loaded on the first and items indicative of a low UBIS (l1–l4) loaded on the second factor (all primary loadings >.5, all secondary loadings <.2). The factors correlated weakly (r = .19) with outliers included and moderately (r = .35) with outliers excluded. Based on this pattern of results, we conclude that it is premature to draw final conclusions on the dimensional structure of the UBIS-8 scale. UBIS could either be conceptualized as comprising (a) one dimension, (b) two weakly correlated dimensions, or (c) two moderately correlated dimensions. As a result, we computed three mean scores: UBIS-8 (all 8 items, Cronbach's alpha = .70), UBIS-l4 (items l1–l4, Cronbach's alpha = .72), and UBIS-h4 (items h1–h4, Cronbach's alpha = .80).

UBIS-1 was a single-item measure (see Appendix A). The two endpoints reflected the prototypic description of the two UBISs as proposed by Rahmati and Zhong (2009). UBIS-1 strongly correlated with UBIS-8, $r = .61$, $p < .001$ (UBIS-l4: $r = .43$, $p < .001$, UBIS-h4: $r = .48$, $p < .001$). Data were available for $n = 76$ users. UBIS-1 was also administered at T1 in S2 to test for temporal stability (correlation with UBIS-8: $r = .57$, $p < .001$, UBIS-l4: $r = .37$, $p = 022$, UBIS-h4: $r = .46$, $p = .003$, data available for $n = 40$ users). UBIS-1 was also administered for users' mobile phone (T2 in S1 and T0 in S2, $n = 78$) and combustion vehicles (CVs, only T0 in S2, $n = 39$). For the last two items, users were also asked to indicate battery life in hours/days and range in km, respectively.

2.3.3. Logger data on charging

Charge level variables were also assessed with data loggers in the EV by the BMW Group. We identified charging events by a SOC increase >12 percentage points between two consecutive trips in order to safely distinguish between charging events and battery recovery. Moreover, charging events were only included in the analysis if they were initiated by the main user[2] and did not occur during the first two months of EV use, as we were only interested in everyday charging behaviour of adapted EV users. Users who had very few available data points (<20) were excluded from the analysis, as we aimed to compute parameters of their individual charge level distributions. Given these constraints, data of $n = 57$ users were determined to be suitable for analysis.

For each user, two parameters of his/her individual distribution of charge level values at start of charge (CLstart) were computed. First, we computed the standard deviation of CLstart values (CLstartSD) because Rahmati and Zhong (2009) proposed that users with a lower UBIS should have a broader distribution (i.e., higher variance) of CLstart values. Second, we computed whether CLstart values were equally or normally distributed (CLstartKS), as Rahmati and Zhong (2009) proposed that user with a lower UBIS should exhibit an equal distribution, while users with a higher UBIS should exhibit a normal distribution (i.e., with a distinct peak) of CLstart values. This was assessed by computing the *p*-value of the Kolmogorow–Smirnov test (*p*KS) for equal distribution minus the *p*KS for normal distribution. Therefore, a higher CLstartKS (i.e., the more the distribution approximates an equal rather than a normal distribution) indicates a lower UBIS and vice versa. Similar to the charging diary, CLstartSD and CLstartKS were assessed in terms of both, SOC and remaining range. Again, these score variants correlated strongly ($r_{\text{CLstartSD}} = .91$, $r_{\text{CLstartKS}} = .70$) and were therefore combined using a factor score. Finally, we also computed the average CLstart value for each user (CLstartM_DL) in parallel to the procedure applied to the charging diary data ($r_{\text{CLstartM\_DL}} = .96$).

2.3.4. Comfortable range

The composite variable of comfortable range incorporated three subscores (see also Franke & Krems, 2013). First, the range game assessed the individual range comfort zone using a standardized and ecologically valid scenario (i.e., 60-km trip in a mostly urban area). Participants were asked to report their comfort level for embarking on a trip, according to four items. This was done 10 times with displayed range values between 45 and 90 km in randomized order. The resulting score value represents the lowest range value that users experience as completely comfortable (for further details see Franke, Neumann, et al., 2012). Second, the 4-item threat scale of the Primary Appraisal Secondary Appraisal (PASA) questionnaire (Gaab, 2009) assessed range threat appraisal for a situation where remaining range and trip distance were equal. Third, the minimum range safety buffer was assessed as the range level below which users were no longer willing to drive the EV. Variables were reverse coded so that high values indicated high comfortable range. A composite score was derived using principal-axis factor analysis (clear single-factor solution, eigenvalue of first factor = 1.62, second factor = 0.81). The three variables had acceptable factor loadings: range game comfort zone = .65, range threat appraisal = .37, range safety buffer = .66. Data were available for $n = 73$ users.

2.3.5. Mental model of range dynamics

Our assessment of users' mental models of range dynamics was based on the conceptual notion that the ability to generate precise situational models in terms of prediction of system states is a valid indicator of a mental model's precision (Endsley, 2000). Users were presented with the following scenario: A range of 100 km was displayed after having driven the last 30 km (the reference distance for the range display in the EV) at an average of 60 km/h in light urban traffic at 10 °C ambient temperature, interior heating set at 20 °C, and low beam turned on. Users estimated displayed range and reported a confidence rating (0–100%), given that they had driven the last 30 km: (1) without regenerative braking, (2) on the motorway at 120 km/h, (3) without heating, (4) without low-beam, (5) at only 45 km/h, (6) with the radio on. The six confidence ratings had a Cronbach's alpha of .95. This measure was assessed at T1, only in S2, $n = 39$.

[2] Several users did not use the personalized car keys as prescribed and were therefore excluded from the analysis as charging events by the main user could not be identified for those participants.

2.3.6. Range utilization

To assess range utilization, users were asked to report their longest distance driven with one charge in the periods between T0–T1 (at T1) and T1–T2 (at T2). There was considerable variance in range utilization: M_{T1} = 132 km, SD_{T1} = 37.6, Min_{T1} = 50, Max_{T1} = 245; M_{T2} = 128 km, SD_{T2} = 28.7, Min_{T2} = 52, Max_{T2} = 212. The correlation of T0–T1 and T1–T2 data was moderately positive, r = .39. A mean score was computed from T1 and T2 data to obtain an estimate of range utilization over the whole trial, n = 77.

2.3.7. Wind-to-vehicle efficiency

The EMS incorporated a controlled charging system to optimize the use of excess energy from wind (wind-to-vehicle). The basic functionality and purpose of the system was explained to the users at T0. This system incorporated an algorithm which regulated energy input during charging to fit the supply curve of excess energy from wind (Westermann, Agsten, & Schlegel, 2010). In particular, this algorithm shifted the charging processes to the time periods when charging would be most "green" (green windows). Therefore, users were asked to set a standard time of the day (e.g. 8 am) at which the car must be fully charged via a website. They could also set exceptions (e.g. Mon, 01/03/2011, 9 am). If users did not set a standard time a conservative default value was used by the algorithm (7 am). For every charging event, the algorithm optimized the charging (a) to take place in green windows, when the available level of excess-energy from wind was high, and (b) to be completed until the standard time set by users. Users could also use the website to deactivate controlled charging for the current charging event and command the system to charge instantly.

Data on wind-to-vehicle efficiency was collected by partners in the field trial project at the TU Ilmenau (Westermann, Agsten, et al., 2010). The wind-to-vehicle efficiency score was available for n = 74 users. The information for the score was automatically recorded in the controlled charging system. The amount of energy charged within green windows (i.e., when excess energy from wind was available) was divided by the total amount of energy charged to yield the indicator of wind-to-vehicle efficiency. This was based on the assumption that higher excess energy from wind during charging is associated with a smaller EV ecological footprint. Of course, for users who tend to charge the car frequently with relatively high remaining energy (e.g., users with a lower UBIS), the time slot actually required for charging the battery would be relatively short. Thus, the algorithm could more easily match the required charging time to the green windows. Therefore, a lower UBIS is expected to be associated with more efficient (i.e., sustainable) use of excess energy from wind. However, it could also be possible, that some users are highly motivated to support controlled charging and adjust their behaviour (i.e., charge as often as possible), which could partly determine their UBIS. Yet, our data did not suggest that this potential influence was present in our sample: There was one item in the charging diary that assessed charging motivation. Users were asked to allocate 100 points to five categories ("I want to support controlled charging.", "There is a possibility to charge.", "I need additional range for my next trip(s).", "low battery", "other"). For 60% of recorded charging events, controlled charging did not receive any points (only for 9% >50 points). Moreover, the users average rating of the category was not related to UBIS-8 (r = −.06).

3. Results and discussion

3.1. Experience of EV charging

Regarding research question (Q1), results at T1 (n = 79) revealed that most users (87%) agreed (dichotomization of 6-point Likert scale) that charging was easy. However, several users (57%) reported that handling the charging cable was cumbersome. Most users (78%) were not bothered by the longer time required for recharging relative to refuelling a conventional vehicle. Seventy-one percent of users preferred to recharge at a charging station (private or public), rather than refuel their vehicle at the gas station. Although 86% of users agreed that public charging stations were indispensible for charging their EV at T0, only 62% agreed at T1. Taken together, it can be concluded that charging was not a major barrier for users in this study.

3.2. Everyday charging patterns

Regarding research question (Q2), results revealed the following: The average daily distance driven with the EV in a typical week, as assessed with the travel diary, was 38.0 km (SD = 20.4). Interestingly, this number is similar to the average daily distance travelled in German urban areas, 36 km (infas & DLR, 2010). This gives some indication that our sample represented relatively average car users, who drove the EV for similar daily distances as a conventional automobile. The maximum distance that participants were willing to drive with the EV when fully charged was on average 124.9 km (*1st quartile* = 105.0, *3rd quartile* = 140.0, SD = 19.9). Thus, the available range of the EV typically lasted for several days. As the users had daily access to a private charging station, they consequently had abundant charging opportunities. On average, they did not need to charge the EV whenever possible, but could instead adopt their preferred charging style.

Based on the data from the charging diary, the average users reported 3.1 charging events in a typical week (*1st quartile* = 2, *3rd quartile* = 4, SD = 1.5). This self-reported charging frequency is similar to the 2.8 charging events per week, as assessed with car-based data loggers for the present field trial by the BMW Group and also similar to figures found in other countries (Vilimek et al., 2012). Users most often employed their private charging station (83.7% of charging events) and only seldomly public charging stations (4.8%) and normal sockets (11.5%). As depicted in Fig. 3, users typically recharged their EV when there was plenty of range left. Sixty-six percent of users on average charged their EV when SOC was >40% and there was a relatively broad distribution of charge levels. This pattern suggests that users with a lower UBIS were represented in this sample. Moreover, distinct peaks in the distribution of charge levels were observed just above 30% SOC and just above 15% SOC. Both of these peaks corresponded with the thresholds of the two standard charge level warnings (i.e., 30% and 10% SOC, see Section 2.1). This pattern indicates the presence of user with a higher UBIS in the sample. Therefore, the charging diary data indicate that there are some individual differences regarding UBIS within this sample (for a more direct examination, see Section 3.4).

3.3. Temporal and cross-device stability of UBIS

In order to examine research question (Q3), the UBIS-1 was administered at T1 and T2 in S2, to allow for analysis of temporal stability after adaptation to the EV. Results showed that UBIS can be conceptualized as a relatively temporally stable characteristic over a period of 3 months, $r = .65$, $p < .001$, $n = 39$.

Cross-device (i.e., cross-situational) consistency was tested by examining the correlation between users' response to UBIS-1 for charging their EV (T2) and for charging their mobile phone (T2 in S1, T0 in S2). Charging a mobile phone differs considerably from charging an EV in terms of the device and the environment (e.g., number of charging opportunities, consequences of running out of charge, charge duration, etc.). However, because of the assumed general UBI preference UBIS should still be similar (see also Fig. 2). Indeed, there was a significant correlation between the two measures, $r = .24$, $p = .035$, $n = 76$. This finding provides some support for the existence of a general UBI preference variable. Previous research has shown that the everyday battery runtime of a device influences adoption of a particular UBIS (Rahmati & Zhong, 2009). Thus, we also computed the analysis only for those users who had a mobile phone with an experienced everyday battery runtime that was relatively comparable to an EV (i.e., <4 days of estimated battery runtime). In fact, this led to an increase in effect size, yielding a moderate and again significant effect, $r = .32$, $p = .035$, $n = 45$. The test of cross-device consistency to CV refuelling was not possible because of limited variance on the CV-UBIS-1 (T0 in S2): 88% had a scale value of 5 or 6, which indicates a high UBIS. Yet, this is a relevant result in itself as it again supports the hypothesis that a high density of easily accessible, usable, and fast charging opportunities in a user's operating range is associated with a higher likelihood of adopting a high UBIS.

3.4. Charge level distribution and UBIS

The hypotheses were tested using a series of regression analyses (Sections 3.4–3.8). Prior to performing the analyses, we examined if assumptions for (multiple) regression analysis were met according to Stade, Meyer, Niestroj, and Nachtwei (2011). Almost all assumptions (e.g., normal distribution and reliability of variables) were satisfactorily met, except for some individual cases that were identified as outliers, residual z-value > |1.96|. Urban and Mayerl (2008) suggested that results should be presented with and without these outliers. To aid readability, results with outliers excluded are presented only if their statistical significance or effect size magnitude differed considerably (e.g., change from a weak to a moderate effect). As we had directional hypotheses, our tests were one-tailed, except for the omnibus test of whole-model fit in multiple regression in Section 3.5. Effect sizes were interpreted according to the conventions (i.e., weak effect is $r = .10$; moderate effect is $r = .30$; strong effect is $r = .50$; Cohen, 1992). All of the regression analyses were conducted with UBIS-8, as it was assumed to be more reliable than UBIS-1 because of its item count (De Gruijter & Van der Kamp, 2008), most comprehensive, and yielded similar results compared to analyses with the subscales UBIS-l4/h4 (we point out all exceptions, see for example in next paragraph). A table that presents a correlation matrix and descriptive statistics of all variables used in confirmatory analyses is included in Appendix B.

In support of hypothesis (H1), a significant relationship between distribution characteristics of users' charge level at start of charge (CLstart) and UBIS-8 was found (see Table 1). Specifically, there was a significant negative relationship between

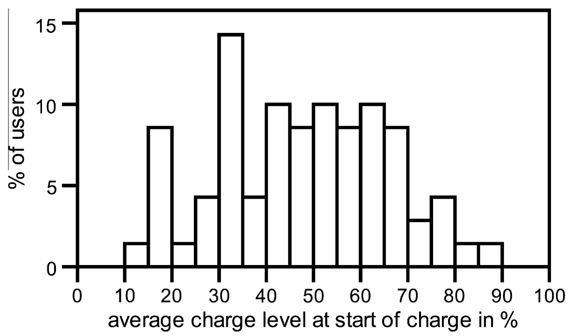

Fig. 3. Histogram of users' average charge levels recorded at start of charge. Data come from the charging diary at T1, $n = 70$.

CLstartSD (the standard deviation of users CLstart values) and UBIS-8 (same result for UBIS-l4). When outliers were excluded, a moderate effect size was observed for this relationship. For UBIS-h4, this effect was not present at first, however, in the analysis with outliers excluded, the result was similar to the result for UBIS-8 (moderate effect). In addition, a significant moderate and negative relationship between CLstartKS (the approximation of CLstart values to an equal minus to a normal distribution) and UBIS-8 was obtained, such that higher UBIS-8 was associated with normal distributions (same result for UBIS-l4/h4). This is consistent with Rahmati and Zhong's (2009) hypothesis that charge level at start of charge is more equally (i.e., broader) distributed for users with a lower UBIS while it is more normally (i.e., distinct peak, narrower) distributed for users with a higher UBIS. Therefore, UBIS is observable in charging behaviour and the UBIS concept seems to be applicable for our purposes.

3.5. UBIS and comfortable range as predictors of typical charging behaviour

Consistent with hypothesis (H2), UBIS-8 and comfortable range explained substantial variance in average charge level values at the start of charge, as assessed by the charging diary and the automatically recorded data logs (see Table 2). The two predictors were significant and in the expected direction in both analyses, with UBIS-8 yielding an (almost) strong effect, and comfortable range yielding a (nearly) moderate effect (similar result for UBIS-l4/h4). These results support our model and the hypothesis that UBIS and comfortable range are two key variables that can explain how users decide to charge an EV.

This result also indicates that the 1-week snapshot of self-reported charging behaviour and the more comprehensive data obtained from the automated data logs yielded very similar results. Indeed, both scores correlated highly, $r = .74$, $p < .001$, $n = 53$. This gives some indication that charging behaviour of EV users in the field trial was temporally stable (i.e., can be assumed to be habitual).

3.6. UBIS and users' confidence in their mental models of range dynamics

In support of hypothesis (H3), there was a significant positive relationship between UBIS-8 and confidence in range estimates (similar result for UBIS-l4/h4), yielding an almost strong effect (see Table 3). As previous literature indicates that range knowledge is related to more efficient utilization of EV range (Franke & Krems, 2013; Franke, Neumann, et al., 2012), the present result provides support for the hypothesis that a higher UBIS is associated with more sustainable behaviour in the usage of EV battery resources.

3.7. UBIS and range utilization

Consistent with hypothesis (H4), UBIS-8 was positively associated with the range utilization indicator, yielding a significant and nearly moderate effect (see Table 4). In the analysis with UBIS-l4/h4 only UBIS-h4 yielded a significant moderate effect. In other words, users who rather charged based on the charge level were also more likely to utilize the full battery resources. Therefore, this result lends additional support to the hypothesis that higher UBIS is associated with more sustainable EV battery usage patterns.

3.8. UBIS and wind-to-vehicle efficiency

As expected from our hypothesis (H5), UBIS-8 was negatively related to wind-to-vehicle efficiency, yielding a significant and, after outlier exclusion, moderate effect (see Table 5). In analysis with UBIS-l4/h4 only UBIS-h4 yielded a significant moderate effect. The relationship implies a goal conflict in terms of which UBIS is related to sustainable behaviour in dealing with the energy resources in the EMS. Implications of this are discussed below.

4. General discussion

4.1. Summary of findings

The present research investigated the psychological dynamics underlying sustainable EV battery charging behaviour. With respect to our research questions, results indicated that: (Q1) Users experienced EV charging as convenient, (Q2) users charged their vehicle about three times a week and typically drove 37 km with the EV per day. Many users typically charged

Table 1
Indicators of (1) a broader (CLstartSD) or (2) more equal than normal (CLstartKS) distribution as predictor for UBIS-8.

		n		*β*		*p*		R^2_{adj}	
(1)	CLstartSD	56	*55*	−.25	*−.32*	.032	*.010*	.05	*.08*
(2)	CLstartKS	56	*54*	−.38	*−.47*	.002	*<.001*	.13	*.20*

Note. Results after outlier exclusion are given in italics.

Table 2
Comfortable range and UBIS-8 as predictors of charge level at start of charge as assessed by the charging diary (1) versus the data logger (2).

		n	R^2_{adj}	*p*	*β*	*p*	Part correlation	Zero-order correlation
(1)	UBIS-8	65	.29	<.001	−.49	<.001	−.49	−.49
	Comfortable range				−.27	.006	−.27	−.28
(2)	UBIS-8	54	.37	<.001	−.51	<.001	−.51	−.54
	Comfortable range				−.32	.003	−.32	−.36

Table 3
UBIS-8 as predictor of users' confidence in their mental model of range dynamics.

n	*β*	*p*	R^2_{adj}
38	.47	.001	.20

Table 4
UBIS-8 as predictor of range utilization.

n	*β*	*p*	R^2_{adj}
75	.28	.007	.07

their EV although substantial battery life was remaining and some users typically charged at charge levels that were associated with battery warnings. These findings suggest the presence of individual differences in participants' UBIS in our sample. (Q3) UBIS was observed to be a relatively temporally stable characteristic that also showed some cross-device consistency. Results of hypothesis testing supported our hypotheses: (H1) charging behaviour in terms of distribution parameters of charge level at start of charge was related to UBIS. (H2) UBIS and comfortable range significantly predicted the charge level at which people typically recharged, (H3) higher UBIS was positively related to confidence in range estimates, and (H4) to range utilization, and (H5) higher UBIS was negatively related to wind-to-vehicle efficiency.

4.2. Theoretical implications

The present research gave some indication for the usefulness of our conceptual model in the prediction of users' charging decisions when interacting with limited EV energy resources (see Fig. 1). Together, UBIS and comfortable range explained up to 37% of the variance in average charge level at which users charged their EV. In addition, the variables were observed to play largely independent roles in this relationship (i.e., small difference between zero-order and part correlation of predictors) and were also found to be nearly uncorrelated in general (see Appendix B). This supports our conceptualization that comfortable range and UBIS are two clearly distinguishable constructs that affect the control loop of UBI (see Fig. 1) at different stages (appraisal versus decision). While comfortable range is similar to the concept of a preferred safety margin or level of accepted task difficulty (Fuller, 2005) that determines how a situation is appraised; UBIS is a preferred decisional style that either (a) orients the user to a specific safety margin and causes the user to not to fill up resources more often than necessary (i.e., engage in safety-related behaviours) or (b) orients the user to fill up resources more often in order to avoid dealing with the safety margin altogether. Although these two variables explain sizable variance, a substantial amount of unexplained variance remains. For example, variables related to the comprehension of the available range buffer and/or additional situational factors might account for part of the unexplained variance. These should be studied in further research.

Moreover our research indicates that the UBIS concept is an important driver of individual differences in users' utilization of limited energy resources. Indeed, our findings suggest that users have a rather consistent battery charging style over time and across devices. Moreover, consistent with previous research (Rahmati & Zhong, 2009), UBIS exhibits relationships with other variables as expected (charge level distribution, mental model of range dynamics, resource utilization). However, given that this is the first quantitative study on UBIS, additional research is needed before drawing firm conclusions from our results. For example, researchers should more directly test whether there is indeed a general UBI preference and future studies should examine which personality factors are drivers of this variable. Some potentially related personality variables could, for example, be: (1) Trust as a facet of agreeableness (Costa, McCrae, & Dye, 1991), because a higher trust in battery resource

Table 5
UBIS-8 as predictor of wind-to-vehicle efficiency.

n		*β*		*p*		R^2_{adj}	
71	*67*	−.21	*−.31*	.041	*.005*	.03	*.08*

Note. Results after outlier exclusion are given in italics.

displays (i.e., the resource estimation algorithm) could lead to higher reliance on this information (i.e., a higher UBIS). (2) Locomotion and assessment (Kruglanski et al., 2000) because these variables are also partly associated with the tendency to avoid cognitive versus motor load. (3) Need for cognition (Cacioppo & Petty, 1982) because this variable is associated with higher acceptance of cognitive load. Moreover, a controlled study of the influence of environmental factors on adoption of a specific UBIS (e.g., the impact of differentially precise battery status displays) would improve understanding of the stability of UBIS.

4.3. Practical implications

Taken together, the results of (H3) to (H5) suggest the emergence of a possible goal conflict. While a higher UBIS seems favourable for sustainable utilization of range resource (H3, H4), it seems unfavourable for sustainable utilization of excess energy from wind (H5). It is difficult to weigh these effects in terms their impact on net sustainability of an EMS. When controlled charging is *not* incorporated in an EMS, a higher UBIS is clearly favourable. When controlled charging is applied in an EMS, a higher UBIS is both, favourable (H3, H4) and unfavourable (H5). A solution to this dilemma could be to introduce and promote controlled charging only after the critical EV adaptation period. Previous research suggests that much of the users' adaptation to range is completed within the first 3 months of EV use (Pichelmann, Franke, & Krems, 2013). It is during this period that range skills, habits and the individual range comfort zone are established. This critical period lays the foundation for efficient range utilization. Consequently, adoption of a higher UBIS should be promoted during these early months of EV use so that users more actively interact with battery resources. Only after the adaptation phase, the more frequent and regular charging patterns should be promoted as they support the utilization of excess energy from wind.

How could the adoption of a specific UBIS be supported? As shown previously (e.g., see Fig. 2), UBIS is not just a function of the person, but also of the device- and environment-related characteristics. A more precise and informative battery indicator and perception of abundant charging opportunities will promote the adoption of a higher UBIS. Rahmati and Zhong (2009) point to the appeal of adaptive charge level displays that increase their precision with lower SOC values. Such displays could reduce *perceived* range depletion and thereby encourage users to wait until they really need to charge. Also, informing users about the location of safety charging spots (i.e., accessible charging opportunities near planned routes that can be used for charging in case of emergency) appears to be a helpful strategy for promoting awareness of the abundance of charging opportunities. Finally, previous research on how users deal with limited EV range showed that prior knowledge regarding EV technology can lead to increased competent range (Franke & Krems, 2013). Given the feedback principles that we assume in our model, knowledge may not only be an outcome but also a predictor of a high UBIS. Frequent and regular charging should only be promoted after users have adapted to range. Although monetary incentives are mostly discussed as motivators to comply with controlled charging (Ifland, Exner, & Westermann, 2011), other motivating factors like intrinsic motivation to use green energy for EV charging appear promising, based on users' responses in the present study (Franke, Bühler, et al., 2012; Rögele, Schweizer-Ries, Zöllner, & Antoni, 2010). Accordingly, employing elements of gamification and competiveness likely represent attractive options in this respect.

4.4. Critical evaluation of study findings and further research needs

Our study results are based on a specific sample of early adopters of EVs, who only represent one segment of all future EV users. However, we assume that the factors underlying the charging behaviour of this group are not fundamentally different from other groups of users, because (1) an influence of socio-demographic characteristics on charging style seems unlikely, and (2) the mobility patterns of users in our sample were relatively similar to those usually found in German urban areas in terms of daily distance travelled. Yet, our sample might be restricted on relevant personality variables as time of adoption is known to be related to personality characteristics (Rogers, 2003). Consequently, the distribution of UBIS values could be different in other samples, as personality is assumed to be a driver of UBIS. Yet, this should not have a substantial influence on the obtained relationships between variables.

Additionally, the present research was conducted using one specific EMS with one specific EV. This control of the device & environment factor (see Fig. 2) was helpful for the present research, as it limited variance associated with extraneous variables. Regarding generalizability, we expect that our results would be similar for other EVs, as the key characteristics of the device, the range of around 170 km and a precise charge level display, are similar to those of other EVs. However, under conditions where the charging network is much less dense (e.g., no daily charging opportunity), or in a sample solely made up of users who approach the objective range limit on a daily basis (e.g., 160 km daily driving distance), results may be different and our proposed theoretical concepts might be less applicable.

In conclusion, we view our research as a first step in achieving a better understanding of everyday charging behaviour in EV users. UBIS seems to be a useful concept in this regard that deserves further research attention. For instance, we believe that a fruitful research agenda could focus on an examination of UBIS from the perspective of the proposed analogy to driving style. Moreover, battery life has also re-emerged as a major usability concern in mobile phones with the rise of smartphones (Rahmati & Zhong, 2009). Hence, we argue, in parallel to other current research (Lundström, Bogdan, Kis, Olsson, & Fahlén, 2012), that it is important to further explore similarities between these two mobile systems and to test the transferability of proposed solutions to the transport domain, for example how to represent energy availability in mobile settings.

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Appendix A

The UBIS-8 scale.

		Im nächsten Abschnitt geht es um **typische Auslöser für das Starten eines Ladevorganges**. Mein Ladeverhalten lässt sich am besten so beschreiben, dass ich **typischerweise geladen habe, wenn…** *The next section is about **typical triggers for starting a charge**. To describe my charging behaviour best, I would say that I **typically charged when**…*	stimmt gar nicht *completely disagree*	stimmt weitgehend nicht *largely disagree*	Stimmt eher nicht *slightly disagree*	Stimmt eher *slightly agree*	stimmt weitgehend *largely agree*	Stimmt völlig *completely agree*
h1	1	… die Batterie leergefahren war. *… the battery was discharged.*	☐	☐	☐	☐	☐	☐
l1	2	… sich irgendeine Gelegenheit zum Laden bot. *… there was any opportunity to charge.*	☐	☐	☐	☐	☐	☐
h2	3	... ich zu wenig Reichweite für meine nächsten geplanten Fahrten hatte. *…I did not have enough range for the next trips I had planned.*	☐	☐	☐	☐	☐	☐
h3	4	… ich eine bestimmte Reservereichweite unterschritten hatte, die ich immer in der Batterie haben wollte. *…I was below a specific buffer range that I always wanted to have in the battery.*	☐	☐	☐	☐	☐	☐
l2	5	… ich in der Nähe einer meiner gewohnten Lademöglichkeit war. *…I was close to my usual charging site.*	☐	☐	☐	☐	☐	☐
l3	6	… eine bestimmte Zeitspanne überschritten wurde, nach der es sich eingebürgert hatte, einfach bei der nächsten Gelegenheit zu laden. *…a particular timeframe had elapsed, after which I had become accustomed to simply charging at the next opportunity.*	☐	☐	☐	☐	☐	☐
h4	7	… der Ladezustand auf ein bestimmtes Niveau abgesunken war. *…the state of charge fell to a certain level.*	☐	☐	☐	☐	☐	☐
l4	8	… ich eine bestimmte Fahrt in meinem Tagesablauf abgeschlossen hatte, nach der es für mich üblich war zu laden. *… I finished a particular trip in my daily routine, after which it was normal for me to charge.*	☐	☐	☐	☐	☐	☐

Note. The leftmost column shows the item IDs and was not displayed in the original questionnaire.

The UBIS 1 item.

Ich lade mein Efzg regelmäßig, ohne weiter auf den Ladezustand zu achten. *I charge my EV regularly without particular attention to the charge level.*	☐	☐	☐	☐	☐	☐	Ich lade mein EFzg immer wenn der Ladezustand unter ein bestimmtes Level fällt. *I charge my EV when the charge drops below a certain level.*

Appendix B

Intercorrelations and descriptive statistics for scores included in the confirmatory analysis and for the UBIS-1 score.

Measures	1	2	3	4	5	6	7	8	9	10	11	12	*N*	*M*	*SD*
1. UBIS-8 (T2)	–												75	4.08	0.85
2. UBIS-l4 (T2)	.73* (75)	–											75	3.71	1.12
3. UBIS-h4 (T2)	.76* (75)	.11 (75)	–										75	4.44	1.16
4. UBIS-1 (T2)	.61* (74)	.43* (74)	.48* (74)	–									76	4.04	1.64
5. UBIS-1 (T1 in S2)	.57* (38)	.37* (38)	.46* (38)	.65* (39)	–								40	3.23	1.62
6. CLstartSD	−.25 (56)	−.36* (56)	−.03 (56)	.02 (56)	.20 (34)	–							57	0.00	1.00
7. CLstartKS	−.38* (56)	−.32* (56)	−.26 (56)	−.33* (56)	−.22 (34)	.27* (57)	–						57	0.00	1.00
8. CLstartM_CD	−.49* (68)	−.38* (68)	−.37* (68)	−.52* (68)	−.48* (33)	.16 (53)	.41* (53)	–					69	0.00	1.00
9. CLstartM_DL	−.52* (56)	−.39* (56)	−.41* (56)	−.60* (56)	−.46* (34)	.13 (57)	.34* (57)	.74* (53)	–				57	0.00	1.00
10. ComfRange	.03 (72)	.02 (72)	.03 (72)	.28* (72)	.09 (39)	.16 (55)	−.21 (55)	−.28* (65)	−.36* (55)	–			73	0.00	0.79
11. Mental model	.47* (38)	.39* (38)	.30 (38)	.22 (38)	.22 (39)	−.20 (33)	−.38* (33)	−.10 (33)	−.32 (33)	.05 (38)	–		39	65.5	14.4
12. Range utilization	.28* (75)	.06 (75)	.35* (75)	.29* (76)	.62* (39)	.13 (57)	−.16 (57)	−.16 (69)	−.39* (57)	.41* (73)	.13 (38)	–	77	129	27.7
13. W2V efficiency	−.21 (71)	−.03 (71)	−.27* (71)	−.14 (72)	−.09 (38)	.04 (53)	.11 (53)	.15 (65)	.19 (53)	−.05 (69)	−.19 (37)	−.15 (73)	74	0.00	1.00

Note. Sample sizes for intercorrelations are given in parentheses. Variables 6.–9. are factor scores and variable 13. is *z*-standardized, therefore $M = 0.00$. Abbreviated score labels: 1.–5. UBIS = user–battery interaction style; 6. CLstartSD = standard deviation of users CLstart values; 7. CLstartKS = the approximation of CLstart values to an equal minus to a normal distribution; 8. CLstartM_CD = mean charge level at start of charge as assessed by charging diary; 9. CLstartM_DL = mean charge level at start of charge as assessed by data logger; 11. Mental model = users' confidence in their mental model of range dynamic; 13. W2V efficiency = wind-to-vehicle efficiency.

* $p < .05$.

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Topical issues

What drives range preferences in electric vehicle users?

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ABSTRACT

While research has shown that limited-range electric vehicles (EVs) satisfy the range needs of a sizeable share of the driving population, car buyers seem to prefer vehicles with high available range. The objective of the present research was to advance understanding of the factors that influence the range preferences of potential EV customers who had the opportunity to test an EV. Data from 79 participants who had driven an EV for 3 months was assessed in a field study setting. Range preferences of those users were found to be substantially higher than their average range needs. Regression analyses indicated that higher average range needs, higher range of the driver′s familiar combustion vehicle (CV), and greater experienced range anxiety were related to higher range preferences. Furthermore, we found that range preferences decreased over the first 3 months of EV use. Finally, indicators of average range needs were more strongly associated with range preferences as EV experience increased. Thus, only customers with EV experience seem to rely on accurate estimates of their range needs when constructing their range preferences. Implications for strategies aimed at enhancing customer appraisal of limited range mobility and determining optimal EV range are discussed.

1. Introduction

What is the optimal range of an electric vehicle (EV)? This question is consistently raised in conjunction with efforts to develop sustainable and marketable EVs, and has yielded substantially disparate answers: evidence suggests that range needs of a sizeable share of the current car fleet could be covered with 100-mile range per charge (Pearre et al., 2011). However, potential customers have repeatedly been found to prefer vehicles with considerably higher available range (Dimitropoulos et al., 2011).

This paradoxical disparity has been noted frequently in the literature (e.g., Giffi et al., 2011; Kurani et al., 1994) and various explanations for high range preferences have been suggested, such as inaccurate conceptions of usual mobility needs (Kurani et al., 1994), high anchors for estimating required range stemming from experience with combustion vehicles (CVs; Kurani et al., 1994), range anxiety (Nilsson, 2011), and lack of experience with limited range mobility (Kurani et al., 1994). However, research that examines these assumptions is lacking. Moreover, it has been argued that examining the range preferences of respondents without EV experience, as most previous studies did, may not be a useful approach for determining truly marketable EV range in more mature markets. Accordingly, researchers have recommended that studies of range preferences should include samples of drivers with EV experience (Kurani et al., 1994).

The objective of the present research was to increase understanding of range preferences of potential EV customers with practical EV experience and of the factors driving those preferences. To this end, a field trial approach was applied in which 79 EV users drove an EV for 3 months and provided extensive objective and subjective data. We studied the disparity between range needs and range preferences and examined potential explanatory variables for range preferences. This research aims to provide data needed to guide the development of measures for reducing the gap between range needs and range preferences, and to support customers in selecting more sustainable EV setups.

2. Background

2.1. The EV range paradox

The battery of a fully electric vehicle is a precious resource. Its efficient layout is critical for environmental utility, as it uses a sizeable amount of energy and rare mineral resources for production and, consequently, has a substantial impact on the ecological footprint of an EV (McManus, 2012). Moreover, more battery capacity results in a higher purchase price and, thus, lower affordability and cost-effectiveness (Neubauer et al., 2012). Hence, from a sustainability perspective, the optimal EV range is the smallest sufficient range.

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Determining sufficient EV range has been the focus of numerous studies examining data on travel behavior. For example, findings based on representative data of everyday automobile usage in Germany show that on a typical day, 95% of cars on the road travel less than 100 km (Öko-Institut, 2011). Similar figures have been reported for other European countries (Bunzeck et al., 2011). However, this criterion has been criticized for underestimating range needs, because a vehicle that can cover an average, or typical, day will not satisfy user needs on many days (Greene, 1985). Consequently, other indicators have been studied, for instance, the longest daily travel distance per year (Greene, 1985; Pearre et al., 2011), per week (Chlond et al., 2012) or on a certain energy critical day (Sammer et al., 2011). Still, these studies show that the currently common 100-mile range of EVs is sufficient for a sizeable share of the car driving population (see overview in Table 1).

However, since acceptance and marketability are fundamental factors of sustainability of EVs, optimal range depends not only on range needs (objectively sufficient range), but also on customer preferences. In previous EV range preference studies, two major methodological approaches have been used (see also Table 2). First, numerous studies used the direct stated preference approach, which requires respondents to indicate a numerical range value that matches a certain utility level (e.g., minimum required range for purchase or minimum acceptable range). For instance, stated preference data for Germany indicate that the average customer wants a range of approximately 340 km (Bunzeck et al., 2011 [328 km]; VDE, 2010 [353 km]). Studies on the European (Bunzeck et al., 2011 [308 km]) and world-wide level (Bronchard et al., 2011 [437 km]) report similar or higher figures.

Second, numerous studies have employed the indirect hypothetical approach with choice-based conjoint analyses (i.e., discrete choice experiments) or contingent ranking tasks. A recent meta-analysis of 31 studies examining customer valuation of driving range (Dimitropoulos et al., 2011) reveals that the compensating variation for increasing range from 100 to 350 miles would be 16,200 US$. The authors conclude that EVs with a 100-mile range would have to be priced 50% cheaper than comparable CVs to be competitive. A similar pattern of results is revealed by Daziano (2013) analysis of choice experiment data. Using the

Table 1
Results from previous studies on range needs.

Study	Sample	Results
infas and DLR (2010)	N=60,713; representative for German population (MiD).	On average, people in Germany travel 39 km per day (one-day travel diary).
Öko-Institut (2011)	Analysis of data collected in MiD 2008 (infas and DLR, 2010).	80% of vehicles travel less than 50 km per day, 95% less than 100 km. On average, 12 trips per year exceed a driving range of 160 km.
Zumkeller et al. (2011)	N=1800; representative for German population (MOP).	On average, people in Germany travel 41 km per day (7-day travel diary).
TÜV Rheinland (2011)	N=1000; considered representative for Germany.	On average, 91% of German respondents drive less than 100 km per day, 61% of them less than 50 km.
Bunzeck et al. (2011)	N=1899 respondents from 7 EU countries.	61% of European participants drive less than 100 km per day, 24% even less than 20 km. 15% drive more than 150 km per day.
Giffi et al. (2010)	$N>$ 13,000 respondents from 17 countries worldwide.	78% of German respondents drive less than 80 km on a typical weekday.
Pearre et al. (2011)	N=484 cars in Atlanta, Georgia greater metropolitan area.	The mean daily driving distance is 45 miles (median: 30 miles). On average, the daily driving range exceeds 100 miles on 23 days per year and 150 miles on 9 days per year. An EV with 100 miles driving range could fully satisfy 9% of the drivers.
Krumm (2012)	N=150,147 US households (representative).	The mean daily distance of US drivers on a random weekday is 38.4 miles. An EV with 60 miles driving range would satisfy 83%, while 80 miles would be suitable for 90% and 120 miles for 95% of the US drivers.

Table 2
Results from previous range preference studies.

Method	Study	Sample	Results
Direct approach	VDE (2010)	N=1000; German residents >14 years of age (representative).	The average German resident considers 353 km driving range to be acceptable.
	ADAC (2013)	N=803 (2011) vs. 507 (2013) ADAC members.	In 2011 74% of ADAC (German automobile club) members desired an EV range of more than 200 km. In 2013, this decreased to 50%.
	Bunzeck et al. (2011)	N=1899 respondents from 7 EU countries.	European respondents require 308 km driving range on average; for German consumers, this figure is somewhat higher (328 km).
	Giffi et al., 2011	$N>$ 13,000 respondents from 17 countries worldwide.	60% of German respondents want an EV to have more than 320 km driving range before they would consider a purchase.
	Bronchard et al. (2011)	N=7003; representative for the general population of 12 countries worldwide.	In order to consider purchasing an EV, people worldwide would prefer to have a range of at least 437 km.
	Zpryme (2010)	N=1046; representative for US drivers.	On average, US drivers consider 294 miles driving range to be acceptable.
Indirect approach	Dimitropoulos et al. (2011)	Meta-analysis of 31 discrete choice and contingent ranking studies.	Compensating variation to extend driving range from 100 to 150 miles is 3500 US$ (16,200 US$ from 100 up to 350 miles). Willingness to pay for one-mile increase in driving range between 47 and 64 US$.
	Daziano (2013)	N=500 California residents.	An EV is perceived as attractive as a gasoline vehicle if its driving range reaches 330 miles. However, if operating costs are integrated into the analysis, the estimate decreases to 180 miles (assuming comparable prices of EV and gasoline vehicle).
	Hoen and Koetse (2012)	N=1802 Dutch drivers.	Willingness to pay for an increase of driving range reaches its maximum in lower range areas, i.e., consumers are highly motivated to avoid low EV driving ranges.

function of range equivalency (i.e., the range at which an EV is perceived to be as attractive as a benchmark vehicle), the author concludes that an EV would only be perceived as equivalent to a conventional gasoline vehicle if its driving range were 330 miles, when cheaper EV operating costs are not considered. If operating costs are factored into the analysis, this estimate would drop to 180 miles (assuming the same purchase price for an EV and a gasoline vehicle).

All in all, these results reveal a substantial discrepancy between range preferences and sufficient range. We refer to this as the "range paradox" in EVs. However, will this discrepancy also hold for future markets that consist of more potential customers who already have experience with limited range mobility? And which factors may influence range preferences in such contexts? Answering these questions may help to yield better estimates of marketable range and aid in the development of strategies to further reduce the range discrepancy.

2.2. The construction of EV range preferences

In order to address the research question regarding which factors might drive range preferences, it is important to understand that preferences often result from a construction process that is vulnerable to various psychological biases (Slovic, 1995). Most importantly, preferences are known to be driven by what comes to mind first (Warren et al., 2011), meaning that the information that is most accessible in memory in a given situation will have the most pronounced impact on the resulting preferences. Accessibility is increased by extensive activation of information (Schwarz, 2007) and by higher associative strength (e.g., caused by more frequent simultaneous activation) between information and the object under judgment (Collins and Loftus, 1975). Hence, if people are very frequently exposed to certain numerical values in connection with driving range, it is likely that those values also drive their range preferences (i.e., act as reference points).

Second, this information more strongly influences a preference that is perceived to be more plausible, relevant, or diagnostic (Warren et al., 2011). Hence, if people have two equally accessible information sources when constructing their range preferences, they will likely more strongly rely on the more diagnostic one (e.g., the more precise indicator of their mobility needs).

Third, affective associations will influence all of these processes. For example, the experience of negative affect (e.g., fear) in conjunction with the object under judgment will lead to more risk-averse preferences (Peters, 2006; Weber and Johnson, 2009). All in all, we expect that these general dynamics in preference formation will also play a role in range preference construction.

2.3. Hypotheses regarding factors that drive range preferences of EV users

(H1) Research has revealed a discrepancy between range preferences and usual range needs in people without EV experience (see Section 2.1), indicating that people might desire certain range safety buffers. Similar safety buffers have also been identified in range utilization behavior of experienced EV users (Franke et al., 2012c; Franke and Krems, 2013). Consequently, we also expect range preferences of *experienced* EV users to be higher than their usual range needs.

(H2) It has been argued that people typically do not hold highly accessible, accurate representations of their usual range needs, as they do not deal with daily distance budgets in using CVs (Kurani et al., 1994). However, when users deal with limited-range electric mobility, they have to manage daily distance budgets and develop heuristics to plan their journeys (Franke et al., 2012c). This should lead to more accessible, precise representations of usual range needs. Hence, it seems likely that experienced EV users use relatively precise estimates of their usual range needs to construct range preferences. Consequently, we expect a positive relationship between usual range needs and range preference in EV users.

(H3) It has repeatedly been argued that people are so adapted to high-range, single-mode CVs that they likely base their judgments of acceptable vehicle range on these highly accessible familiar values (Giffi et al., 2010; Kurani et al., 1994). Indeed, the status quo is known to be a powerful reference point in preference construction (Samuelson and Zeckhauser, 1988). Consequently, we expect a positive relationship between familiar CV range, hereafter referred to as CV performant range (cf. Franke and Krems, 2013), and range preferences.

(H4) Range anxiety has repeatedly been proposed as a factor that promotes high range preferences (Nilsson, 2011). Given the research demonstrating the impact of negative affect on judgment (see Section 2.2), it seems reasonable that experienced range anxiety may be associated with higher range preferences. Consequently, we expect a positive relationship between experienced range anxiety and range preferences of EV users.

(H5) When considering (H2) from a longitudinal perspective, it can be expected that as EV experience increases, precise representations of usual range needs will be more strongly incorporated into range preference construction. Consequently, we expect that as experience increases, the relationship between range needs and range preferences will strengthen.

(H6) Taken together, these hypotheses suggest that experienced EV users should prefer lower range setups than inexperienced users. This is also supported by the finding that the need for safety buffers decrease with EV experience (Franke et al., 2012b). Consequently, we expect that users′ range preferences at post-test (i.e., after driving the EV for some time) will be lower than at pre-test (i.e., before receiving the EV).

3. Method

3.1. Field trial setup

The present research was part of a large-scale EV field trial in the metropolitan area of Berlin, Germany. This trial was set up by the BMW Group and Vattenfall Europe, and funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. It was part of an international EV field trial (Vilimek et al., 2012). The EV was a converted MINI Cooper with 168 km range under normal driving conditions (miniusa.com, 2012). Users had access to public and private charging stations. Two consecutive 6-month user studies (S1 and S2) included 40 participants each. Data were collected prior to receiving the EV (T0), after 3 months (T1), and after 6 months (T2). Data for the present study came only from T0 and T1, 79 users completed T0 and T1. Further details on methodology are reported elsewhere (Cocron et al., 2011; Franke et al., 2012a).

3.2. Participants

Eighty participants were selected from more than 1000 applicants recruited via an online screening instrument that was announced in both print and online media. Requirements for participation were residence in the Berlin metropolitan area, willingness to pay a monthly leasing rate of 400 Euros, and to install a private charging station. Additional criteria aimed to increase variance in basic socio-demographic (e.g., age, gender, education) and mobility-related variables (e.g., mileage, vehicle fleet). Despite these efforts, our sample was still restricted in variance on certain basic socio-demographic characteristics compared to the general population of automobile drivers in Germany (i.e., the average German car driver). The sample can rather be assumed to represent early adopters of EVs in German metropolitan areas.

The 79 users in the sample who completed T1 had a mean age of 49 years. Eighty-five percent were male, 76% had obtained at least a university of applied science entrance qualification (nearly all of these had a university degree), 10% reported a monthly net household income below 3.000 Euro, and the average household size was 2.9 persons (47% of households had <3 persons). To better understand the differences between this sample and the population of German car drivers, we analyzed data from the representative large-scale survey “Mobility in Germany 2008” (Mobilität in Deutschland, MiD; infas and DLR, 2010). We included only those persons who had access to a car at any time (72% of the persons living in Germany) and were at least 17 years old. These had a mean age of 42 years, 51% were male, 40% had at least a university of applied science entrance qualification, 65% had a monthly net household income below 3.000 Euro, and the average household size was 2.4 persons (64% of households had <3 persons). Hence, our sample is older, more affluent, more educated, and includes more male persons than the general population of German car drivers. In terms of average-day travel distances in a typical week our sample had even higher values ($M_{7D}=58.76$ km, only $N=66$, see Section 3.3.2) than the German average of 40.6 km (Zumkeller et al., 2011).

3.3. Measures

3.3.1. Range preferences

Two open-ended, stated preference items asked users to directly indicate their preferred range value underlying two different levels of the utility function. For contexts where incentive-aligned methods are not applicable, it has been shown that single-item, open-ended question formats can be as valid as choice-based conjoint analyses (Miller et al., 2011). Items were framed to the real available range of the test EV. The item text was: (1) "Which EV range would you consider to be quite short, but just acceptable?" (termed “minimum acceptable range”, conceptually similar to a reservation price), and (2) "Which EV range would you consider to be just right and, therefore, appropriate?" (termed “appropriate range”). Both items were administered at T1. In S2, minimum acceptable range was also assessed at T0. This and all following variables were checked for univariate outliers in accordance with Grubbs (1969). One case was an outlier on both T1 variables ($z>4.96$), hence $N=78$, and one case was an outlier on T0 minimum acceptable range in S2 ($z=3.49$), hence $N=39$. The Kolmogorov–Smirnov (KS) test was used to test for violations of normality for all score variables. As one would expect for range preferences (Dimitropoulos et al., 2011), log transformation was needed for the data to fit a normal distribution.

3.3.2. Range needs

Data on range needs were derived from the T0 travel diary, which was a person-based 1-week record of all trips, including all modes of transport. Based on previously proposed range need indicators (see Section 2.1), we computed the mean (M_{7D}) and maximum (Max_{7D}) daily travel distances for the 7-day week (7D), $N=66$ because of 11 cases with missing data and 2 outlier cases ($z>3.29$). We also asked users to mark a typical day (TD) and computed the total distance traveled on that day (Sum_{TD}), $N=56$, as only 57 users marked their TD and there was one outlier ($z>6.38$). Log transformation was needed to fit a normal distribution.

3.3.3. Performant range

Users′ CV performant range was assessed at T0 only in S2 with one item ($N=40$): “How far does one full tank usually last (based on annual average) before the tank is completely emptied in your most used car (km)?”

3.3.4. Range anxiety

Range anxiety was assessed with two items at T1 ($N=79$): (1) “I am more concerned about the range in the EV than I would be in a conventional vehicle with an internal combustion engine.” (2) “While driving, I was often worried about the range.” Cronbach′s Alpha was .62.

4. Results

We analyzed our data using *t*-tests and regression analyses. Assumptions for *t*-tests were satisfactorily met. Assumptions for regression analyses (Stade et al., 2011) were satisfactorily met, except for some non-normal distributions, that were resolved with log-transformation, and some single outlier cases, residual *z*-value $>|1.96|$. Urban and Mayerl (2008) recommended presenting results with and without these outliers. To aid readability, results without outliers are presented only if their significance or effect size magnitude differed considerably from results with outliers. To test our directional hypotheses, we used one-tailed tests. The descriptive statistics for the variables used in the analyses are depicted in Table 3.

4.1. Discrepancy between range preferences and range needs

All difference score variables, except those including Max_{7D}, were normally distributed (KS-test $p>.05$). Therefore, *t*-tests were computed with untransformed variables, except for tests including Max_{7D}, which used log-transformed variables.

In support of H1, range preferences were generally found to be substantially higher than average daily range needs in our sample of experienced EV early adopters. The minimum acceptable and appropriate range values were significantly ($p<.001$) higher than average (M_{7D}) and typical (Sum_{TD}) daily distance, with effect sizes between $d=1.24$ and $d=1.95$ (on average $d=1.61$). The difference between maximum daily travel distance (Max_{7D}) and appropriate range was also strong ($d=.80$, $p<.001$), but the difference between Max_{7D} and minimum acceptable range was weak and insignificant ($d=.20$, $p=.060$). Cumulative distributions of M_{7D}, Max_{7D}, and minimum acceptable range are depicted in Fig. 1. On average, M_{7D} was 58.76 km ($SD=37.40$, $Mdn=44.99$), and Max_{7D} was 149.30 km ($SD=149.24$, $Mdn=81.00$), whereas minimum acceptable range was 135.13 km ($SD=57.93$, $Mdn=120.00$).

Table 3
Descriptive statistics for variables used in the analyses.

	N	*M*	*Mdn*	*SD*	*P25*	*P75*
Range preferences						
Minimum acceptable range T1	78	135.9	120.0	60.1	100.0	155.0
Minimum acceptable range T0	39	144.9	120.0	59.6	100.0	150.0
Appropriate range T1	78	214.5	200.0	89.8	150.0	262.5
Range needs						
M_{7D}	66	60.1	45.6	38.3	35.8	66.7
Max_{7D}	66	152.7	83.5	150.9	63.8	161.3
Sum_{TD}	56	46.7	45.5	26.0	32.1	55.1
CV performant range	39	607.8	600.0	201.2	480.0	700.0
Range anxiety	79	3.4	3.5	1.0	3.0	4.0

Note: The maximum available sample (*N*) is analyzed for each variable. *N* can be smaller when relating two variables in an analysis. Therefore key descriptive statistics are repeated for the final *N* used in the analyses (e.g., Section 4.6). *P25*/*P75* = 1st/3rd quartile.

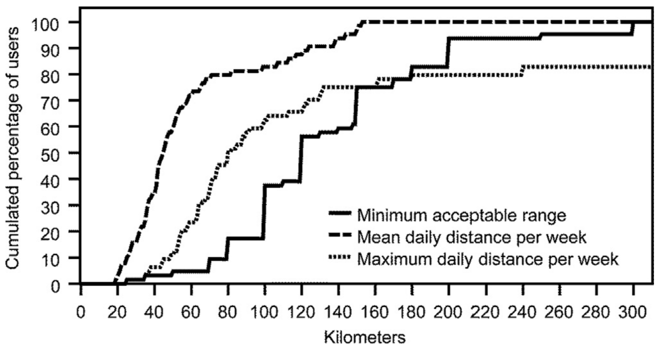

Fig. 1. Cumulative distributions of M_{7D} and Max_{7D} and T1 minimum acceptable range ($N=64$).

Table 4
Range needs as predictor of range preferences.

	N	β	p	R^2_{adj}
M_{7D}				
Minimum acceptable range	65	.31	.006	.08
Appropriate range	65	.27	.014	.06
Max_{7D}				
Minimum acceptable range	65	.33	.003	.10
Appropriate range	65	.31	.005	.08
Sum_{TD}				
Minimum acceptable range	56	.22	.053	.03
Appropriate range	56	.24	.040	.04

Note: *P*-values are one-tailed.

4.2. Objective range needs as predictor for range preferences

In support of H2, usual range needs were moderately, positively associated with range preferences of experienced EV users (see Table 4). Hence, experienced EV users indeed seem to incorporate range needs in range preference construction. There were no differences in explanatory power between M_{7D} and Max_{7D}. Yet, the typical day measure (Sum_{TD}) was less effective in predicting preferred range. Hence, it seems that multi-day range need indicators are required to estimate an individual's preferred EV range.

4.3. CV performant range as predictor of range preferences

In support of H3, the performant range of the participants' most used CV was found to be moderately positively associated with range preferences (i.e., significant effect for all variables without outliers, see Table 5). It seems unlikely that the CV range effect is caused by pre-existing higher range needs that lead to ownership of higher range CVs, as the relationship between these two variable sets was relatively weak (average $r=.14$).

4.4. Range anxiety as predictor of range preferences

In support of H4, range anxiety was positively associated with experienced EV users' range preferences (see Table 6). Effect sizes were (almost) moderate. Further, range anxiety did not appear to be a proxy variable for range needs (higher range needs = more experience of range anxiety), as these two variable sets were only weakly correlated, and in a negative direction (average $r=-.12$). This increases the likelihood that individual differences in range anxiety are driven by different subjective experiences of similar range situations, rather than different exposure to critical range situations.

Table 5
Familiar CV performant range as a predictor of range preferences.

	N		β		p		R^2_{adj}	
Minimum acceptable range	39	*37*	.19	*.32*	.125	*.029*	.01	*.07*
Appropriate range	39	*37*	.27	*.33*	.047	*.024*	.05	*.08*

Note: Results after outlier exclusion are given in italics, *p*-values are one-tailed.

Table 6
Range anxiety as predictor of range preferences.

	N		β		p		R^2_{adj}	
Minimum acceptable range	78	*73*	.28	*.36*	.007	*.001*	.07	*.12*
Appropriate range	78		.27		.009		.06	

Note: Results after outlier exclusion are given in italics, *p*-values are one-tailed.

Table 7
Range needs as predictor of range preferences.

	N	β	p	R^2_{adj}
M_{7D}				
T0: Minimum acceptable range	35	.14	.204	−.01
T1: Minimum acceptable range	35	.45	.003	.18
Max_{7D}				
T0: Minimum acceptable range	35	.07	.340	−.02
T1: Minimum acceptable range	35	.42	.006	.15

Note: *P*-values are one-tailed.

4.5. Effect of practical EV experience on the relationship between range needs and range preferences

In support of H5, usual range needs were moderately associated with range preferences of experienced EV users (T1), yielding a significant effect, but were not associated with range preferences of the same users before EV experience (T0) (see Table 7). As a direct test of H5, we tested whether the correlation between M_{7D} and T0 minimum acceptable range (r_{T0}) was stronger than the correlation between M_{7D} and T1 minimum acceptable range (r_{T1}), according to Meng et al. (1992). This test revealed a significant difference ($p=.040$, for Max_{7D} $p=.025$), indicating a stronger relationship with increasing EV experience.

4.6. Effect of practical EV experience on range preferences

In support of H6, minimum acceptable range was found to be higher at T0 ($M=144.87$ km, $SD=59.64$) than at T1 ($M=123.97$ km, $SD=60.69$), revealing a relatively small ($d=.32$) but significant effect, $t(38)=-2.02$, $p=.025$. Untransformed variables were used, as the difference score T0–T1 could be assumed to be normally distributed. However, a similar result was obtained with log-transformed variables, $d=.45$, $t(38)=-2.84$, $p=.004$.

5. Discussion

The present research sought to better understand factors that influence range preferences in potential EV customers with EV experience. In general, our assumptions were supported: (H1) range preferences were found to be substantially higher than typical and average daily range needs, but not much higher than weekly maximum daily range needs. (H2) Usual range needs were positively related to range preference of experienced EV users. (H3) Familiar CV performant range was associated with higher range preferences. (H4) Experienced range anxiety was associated with higher range preferences. (H5) Usual range needs were more strongly associated with range preferences with increasing EV experience. (H6) Range preferences decreased with EV experience.

5.1. Implications for understanding and resolving the EV range paradox

The discrepancy between average range needs and range preferences in our study is consistent with previous findings (see Section 2.1); though, our effects appear smaller than those reported in previous studies. This might be partially attributable to the decrease in range preference associated with increased EV experience (H6), but it might also partly be attributable to our sample of early adopters, who are known to accept potential usage barriers more readily (Rodriguez and Page, 2004). Hence, the discrepancy between range needs and range preferences might be larger in the future general population of experienced EV drivers than was observed here. However, given that there are some indications of decreasing EV range preferences in the general population over the last several years (see study of ADAC, 2013 reported in Table 2), this might also not be the case. Importantly, our findings indicate that early EV buyers may not, on average, request exaggerated range setups, because their minimum acceptable range was similar to their weekly maximum daily range needs.

Our findings suggest that average and maximum usual range needs only act as a reference point in preference construction for experienced EV drivers. The weak effect for inexperienced drivers is consistent with previous research (Bunzeck et al., 2011). However, is it really plausible that potential customers without EV experience do not anchor preferences on their range needs at all? It might be that they do not use *accurate* estimators of their range needs; instead, they may only use highly accessible indicators, such as a critical destination or most recent holiday trip, which do not accurately represent usual range needs. Future research identifying these alternative reference indicators in people without EV experience may help to inform strategies for reducing range discrepancy by, for example, fostering users′ understanding of the low diagnostic value of certain highly accessible range need indicators. It might also be possible to establish accurate representations of range needs in users without 3 months of limited range mobility experience. However, filling out a travel diary alone is likely not sufficient to accomplish this objective, as users also did this before the T0 range preference assessment in the present study and there was no indication that participants relied on those recorded values. Yet, providing detailed individual feedback on the results of such a diary could already be sufficient for producing a measurable effect on range preferences.

From a methodological perspective, these findings also suggest that collecting data on travel patterns over a 1-week period is sufficient to derive meaningful estimates of average range preferences in future EV markets with more experienced users. The necessity of using multiple-day, instead of single-day data, to derive meaningful estimates of optimal range is supported by the high correlation between multiple-day range need scores and range preferences and the relatively weak correlation between the typical-day range needs and range preferences.

The obtained relationship between experienced CV range and range preferences indicate that familiar vehicle range likely acts as a reference point in range preference construction. However, based on our results, it seems unlikely that only a few months of driving a limited-range vehicle will replace the representation of high-range CVs, which users have experienced for years as the status quo of vehicle range. This should be true, at least, when users sometimes still use a conventional car, as in our study.

Range anxiety is another moderator variable that should be taken into account when considering strategies to reduce the range discrepancy. People who experience more (anticipated) range anxiety may need more support in coming to view lower range values as acceptable. An important next step will be to better understand the psychological variables that influence range anxiety.

Finally, the decrease in range preference over the first 3 months of usage suggests that practical experience with limited range mobility could play an important role in increasing acceptance and purchase intentions. This is also supported by related research that has found an increasing perceived fit between mobility needs and EV mobility resources over the first 3 months of EV experience (Franke et al., 2012b). However, the potential of short-term experience on range appraisal has yet to be quantified because adaptation to EV range seems to take several weeks (Pichelmann et al., 2013). It might be that this time of adaptation (i.e., the learning process) can be shortened, for example, by motivating and supporting users to actively explore and exhaust the range. This could be achieved with advanced driver information and assistance systems that help users to extend the range and reduce uncertainty regarding the sufficiency of the remaining range for upcoming trips. A critical task for future research will be to examine the changes (i.e., adaptation effects) in range preferences that are caused by EV experience more in depth.

5.2. Critical evaluation of study design and findings

The present study was among the first to examine factors influencing range preferences of potential EV customers who had experience using a realistic electric mobility system. In interpreting the results, several critical issues must be taken into account. Given the field study research design, inferences about causal relationships cannot be easily drawn. Future studies should be conducted to determine whether the associations reported here are causally related. Moreover, replication studies with larger sample sizes are needed to test for the robustness of the present results.

Furthermore, our study results are based on a specific sample of early adopters of EVs, who are likely not representative of all car buyers. However, we believe that understanding this target group is of essential importance as it represents a wellspring for EV market penetration. Moreover, the factors influencing range preference observed in this sample of experienced users may also generalize to more mature markets, which include fewer first time buyers and more experienced EV drivers.

Finally we did not take into account several factors that affect mobility resources in an electric mobility system, such as recharging infrastructure (i.e., density and recharging time) and user access to other mobility options. These elements of an electric mobility system have the potential to act as technical safety buffers, facilitate coping with limited EV range, and therefore potentially leading to lower range preferences. Future research should empirically test the effects of these factors on range preferences.

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12/2011 - 05/2012	BMW ActiveE Berlin (Projektakquise, Projektmitarbeit)
07/2012 - 06/2015	EVREST - Electric Vehicle with Range Extender as a Sustainable Technology (Projektakquise, Projektleitung)
12/2012 - 02/2015	BMW ActiveE Leipzig – Kundenakzeptanz Elektromobilität bei erhöhter Reichweitenanforderung – Langstreckenpendler (Projektakquise, Projektleitung)

Lehre

WS2011/12 WS2012/13 SS2013 WS2013/14	Empirisch-Experimentelles Forschen
SS2012	Seminar Toolbox Arbeitspsychologie und Ergonomie

VII Publikationen

Zeitschriftenartikel (peer reviewed)

Cocron, P., Bühler, F., Franke, T., Neumann, I., Dielmann, B., & Krems, J. F. (2013). Energy recapture through deceleration–regenerative braking in electric vehicles from a user perspective. *Ergonomics, 56*(8), 1203-1215. doi: 10.1080/00140139.2013.803160

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Bühler, F., Franke, T., Schleinitz, K., Cocron, P., Neumann, I., Ischebeck, M., & Krems, J. F. (2014). Driving an EV with no opportunity to charge at home - is this acceptable? In D. de Waard, K.

Brookhuis, R. Wiczorek, F. di Nocera, R. Brouwer, P. Barham, C. Weikert, A. Kluge, W. Gerbino, & A. Toffetti (Hrsg.), *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2013 Annual Conference*. Abgerufen von: http://www.hfes-europe.org/books/proceedings2013/Buehler.pdf

Bühler, F., Neumann, I., Cocron, P., Franke, T., & Krems, J. F. (2011). Usage patterns of electric vehicles: A reliable indicator of acceptance? Findings from a German field study. *Proceedings of the 90th Annual Meeting of the Transportation Research Board.* Abgerufen von http://amonline.trb.org/12jj41/1

Bühler, F., Neumann, I., Cocron, P., Franke, T., Krems, J. F., Schwalm, M., & Keinath, A. (2010). Die Nutzerstudie im Rahmen des Flottenversuchs MINI E Berlin – Methodisches Vorgehen und erste Erfahrungen im Rahmen der wissenschaftlichen Begleitforschung. In T. J. Mager (Hrsg.), *Mobilitätsmanagement – Beiträge zur Verkehrspraxis* (S. 81-96). Köln, Deutschland: ksv-verlag.

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Cocron, P., Bachl, V., Neumann, I., Franke, T., Bühler, F., & Krems, J. F. (2011). Die geringe Geräuschkulisse von Elektrofahrzeugen: viel Lärm um nichts?. In K. Bittrich, S. Blankenberger & J. Lukas (Hrsg.), *Beiträge zur 53. Tagung experimentell arbeitender Psychologen* (S. 33). Lengerich, Deutschland: Pabst Science Publishers.

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Eidesstattliche Erklärung

Die vorliegende Arbeit wurde von mir selbstständig verfasst.

Ich habe keine anderen als die angegebenen Hilfsmittel benutzt.

Thomas Franke

Chemnitz, den 30.10.2013