Experiencing Range in an Electric Vehicle - Understanding Psychological Barriers

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ABSTRACT

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 utilization. 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.

Keywords: range, electric vehicles, field study, traffic and transport psychology, Germany

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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 purchase 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 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, et al., 1998; Goldstein, Koretz, & Harats, 1996), and few have examined overt user behavior or general user satisfaction with EVs (Eden, 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 underutilize 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.

Psychological Range Levels in an EV

To characterize the nature of range experience and range utilization, 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 standardized 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 characterized 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 optimization 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 utilize. 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.

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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.

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 & 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 & 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

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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 characterize 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).

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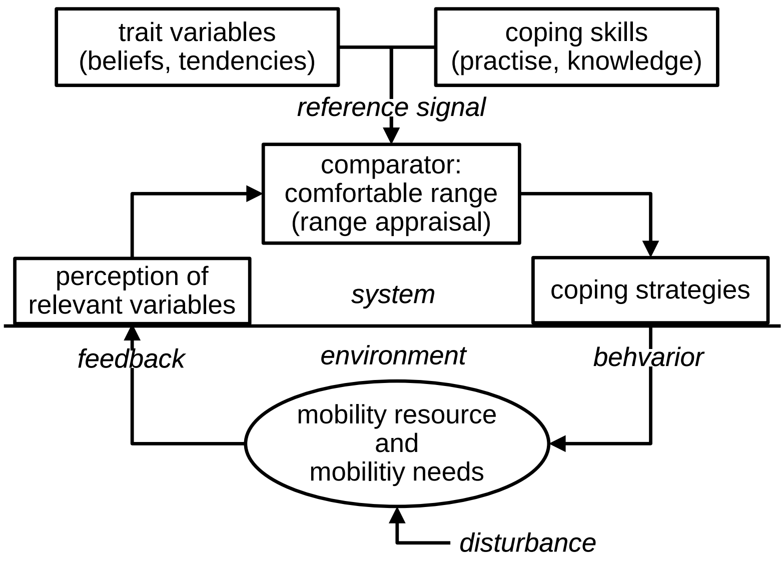

FIGURE 1. Conceptual framework for comfortable range. At the micro-level of range adaptation, mobility resources, such as remaining range and recharging opportunities ahead are plotted against mobility needs to produce a perceptual signal. This signal is then compared to reference signal variables (e.g., 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.

To sum it up, we have pointed out that range experience in experienced EV drivers is an important topic but is poorly understood. Giving 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 is: What is the role of stress-buffering personality traits and coping skills in comfortable range? We hypothesize 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.

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METHOD

Field Study Setup

The present research was part of a large-scale EV field trial in Berlin metropolitan area in Germany. This trial was set up by BMW Group and Vattenfall Europe and 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 2h to 3h 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, et al., in press; Franke, Bühler, Cocron, Neumann, & Krems, 2011; Krems, et al., 2010)

Participants

Participants were recruited via an online screening application that was publicized 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 which were male, 78 % had a university degree, and 25 % had completed a doctoral degree. The majority (78 %) of user households consisted of two people > 18 years of age (43 % had children). In 58 % 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.

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 characterized 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.

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 & 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 asses 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 (EV was a two-seater with 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 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.

Measures of Range Appraisal and Comfortable Range

Range game. The aim of the range game was to precisely assess the individual comfort zone in a standardized, yet ecological valid way. The naming 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 possibilities along this route. Afterwards, they received 10 four-item questionnaire cards in random order, including the same four items but differing information about 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 was checked for extreme outliers as a few participants had problems with double negation in the last item above. For two persons 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 operationalization of a user’s individual range comfort zone for the corresponding standard situation provided in the game. The range game was administered at T1.

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, et al., 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 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).

*Maximum comfortable trip distance.*To directly assess range resources that users were comfortable with utilizing 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.

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.

Measures for Stress-buffering Personality Traits

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 conceptualized 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).

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).

Measures for Stress-buffering Coping Skills

Subjective range competence. The subjective individual skills for coping with (remaining) range of an EV were measured by 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 on." 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).

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 nation-wide travel surveys (Kunert & Follmer, 2005). The diary was a person-based record of all main-user EV trips. Only the data of the T1 travel diary was used because there were too much 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 of the five weekdays was 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-standardized variables.

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 on 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.

Range Experience Qualities in an EV

For the interview question "How have you experienced the range of the EV?" answers of 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 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 generalized 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 (3 of 7 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 brought forth 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 categorized to regard 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.

Quantitative Indicators of Range Experience

Concerning range satisfaction 90 % of experienced users agreed (dichotomization 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 % 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 % of users never experienced such a situation, 18 % experienced it at least once but less than once a month, 24 % of the users indicated once a month, and 24 % 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 utilization 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.,

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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 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 to use 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 utilize around 80 % 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-standardized 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-standardized 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).

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 if 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 multicolinearity 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 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.

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)

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 hypothesized predictor variables.

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 skills model) without outlier cases; p-values are one-tailed.

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 highly prominent in EV use. Most users rarely ran into situations where they felt stressed or nervous as a result of range.

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Although users worried more about range than they would have in a conventional car, these worries occurred relatively infrequently. According to 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 utilization for many users. Of course, low range utilization 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 utilization should be enhanced in present and future electric mobility systems. Yet, enhancing potential range utilization 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 utilization. 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 utilization and range experience. In sum, the examined protective variables proved fruitful in advancing our understanding of the dynamics of range appraisal and comfortable range.

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 to 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 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, et al., 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 coming years. In fact, EVs currently in development offer ranges suitable to a major share 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 utilization 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 utilizations. This is the basis for discovering feasible approaches to enhancing usable range for electric mobility users. Based on the current findings, instead of simply maximizing 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.

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 contextualized 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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