User-Centred Design of an Audio Feedback System for Power Demand Management

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Abstract. Low-income houses in South Africa are supplied with a pre-payment meter and a circuit breaker that trips at a low power level (about 20A, 4.5kW), resulting in many nuisance trips. Four categories of audio cues, each being able to represent five levels of power consumption, are assessed. A survey of 62 people was conducted. The numerical analysis of the results and the perceptions of the respondents both indicate that the use of changing tempo and texture is the most effective at conveying feedback information on the power consumption in the home.

Keywords: audio cues, demand management, low cost, energy feedback.

1 Introduction

This paper addresses the issue of developing a design methodology for providing immediate and intuitive audio feedback about high power consumption to low-income residential users, particularly for periods when their demand is approaching the maximum capacity of the main circuit breaker in their home.

On any electrical power system (national grid, microgrid or nanogrid) it is extremely important that the flow of power between generators and loads is balanced at any instant in time. This ensures stable operation of the system and avoids the disruption that will ensue if the grid is blacked out due to instability. Stability can be addressed from the generation side as well as the consumption side. An adequate reserve margin on the generation side (embodied in the kinetic energy of the spinning turbo-generators, or stored battery charge on microgrids) gives the grid operators the freedom to dispatch more energy from the generators to the load side at short notice. South Africa in particular is facing severe generation constraints at the present

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moment in time; the generation reserve margin of the national utility company, ESKOM, was as low as 0.17% on 13 May 2013 [1].

Load side response (better known as demand side management) is now coming to the fore, as it has been demonstrated that it can be more economical than expanding the generation side [2]. However, demand side response is challenging because it requires that a large number of consumers actively participate. In South Africa, national campaigns are in place to encourage households to swap incandescent lights for more efficient lighting solutions and consumers are being offered rebates on solar water heaters [3]. Furthermore, real time alerts are displayed on state-owned television channels to reduce peak demand; this visual information system takes the form of a special graphical display at the bottom of the television screen that indicates the current demand status to households via the use of colours and bar charts. The scheme provides information to consumers about the state of the grid, and has been shown to have an impact at a national level [4], but it does not tell consumers much about their own contribution to the total demand. This is a problem because many residents in rural areas often have their power consumption limited by pre-paid electricity meters equipped with feed-in breakers, as shown in Fig. 1. These breakers trip at a modest level of 20A [5], frequently cutting off the power supply with no warning.

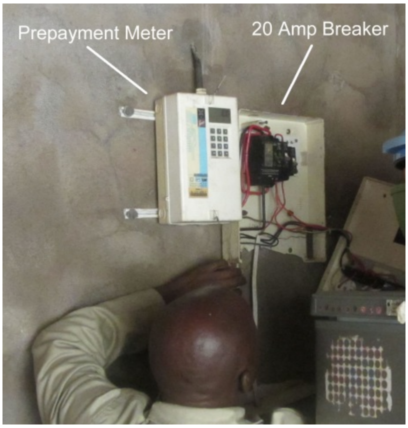


Fig. 1. A typical installation showing the pre-payment meter and 20A breaker

Although there is the occasional use of automation to disconnect hot water systems during periods of high power demand [6], this intervention is often not sufficient to prevent the breaker from tripping. Further intervention is frequently necessary, but the automation of additional household appliances becomes complex and is too expensive, especially given that most residences equipped with prepayment meters and feed-in breakers are low-income households.

However, site visits revealed that the combination of their low income and use of prepayment meters has made these residents both aware of their household energy usage and motivated to take action to reduce consumption and prevent tripping of the breaker. As there is a strong motivation amongst the community [7] this context presents an ideal case for integrating users into the demand management process. Feedback about household electricity demand is thus explored as a mechanism for encouraging and enabling users to better manage their energy consumption and prevent power outages.

This paper focuses on assessing the efficacy of cues to the user that enable them to manage their demand and limit high levels of energy consumption by prompting immediate action when the load approaches the trip level. Specifically, it addresses the question of which parameters within the cues produce consistent, accurate and meaningful responses from users. The work presented here does not include the deployment of any technologies into the field.

First, the relevant literature is explored to determine key aspects in the design of effective feedback mechanisms for demand management, and Section 2 concludes that, in general, user-centric design needs to fulfil four criteria. In Section 3 the specific context of this work is examined, particularly the need for users to respond immediately to the feedback to prevent power outages, and thus audio cues are suggested as an appropriate mechanism. Users also need to be made aware of situations when their use is approaching high power consumption (i.e. before it reaches maximum capacity), therefore we propose that a suite of cues is required. Section 4 discussed the design of these cues, and Sections 5 and 6 present findings from preliminary testing. Conclusions and recommendations for further research are discussed in Section 7.

2 Feedback as a Mechanism for Demand Management

Feedback about energy consumption has been used over the past 40 years as an effective mechanism for encouraging energy demand management. Feedback interventions are on the whole effective at encouraging users to reduce consumption, and they are cost effective when compared to other interventions [8]. However, the way that users respond to feedback varies significantly, and whilst feedback is effective on average, it is not so in all cases [9]. A more recent body of work in this space points to the importance of considering users when designing feedback interventions, particularly with regard to their interaction with the feedback technology [10,11].

Although the provision of energy consumption information is of considerable value, for the feedback system to be effective at bringing about the desired shift in energy behaviour it is important that the design process accounts for the way in which users interpret and respond to the feedback, as well as their behavioural and motivational psychological aspects in relation to energy use [12]. In addition, contextual constraints can limit a person's ability to respond to feedback regardless of their motivation to act [13], and therefore careful consideration of the specific purpose of the feedback, the context in which energy is being consumed, and the Living Standards Measure grouping and cultural background of the target demographic is important.

A key challenge is to develop a user-centric design of a system capable of providing households with real-time feedback about their consumption that meets the following four design criteria: (1) it is appropriate to the specific context in which it is intended to be used, (2) it is interpreted consistently and accurately, (3) it provokes a response at the appropriate point in time, and (4) it is positively perceived by the user. The context for this study is different from most feedback studies and therefore needs closer examination and is addressed in the next section.

3 The Case for an Audio Cue

Most feedback interventions aim to encourage consumers to reduce their overall energy consumption, and are designed and evaluated accordingly. However, these systems are not appropriate when trying to encourage reductions in peak usage, where the main concern lies around the simultaneous use of a number of high power appliances, leading to a power trip. This raises four issues.

Firstly the user response has to be immediate. Energy consumption is a measure of power demand aggregated over time and hence the timing of the feedback to the user is not critical. For this case the user can ‘pull’ the feedback from the device. However for peak power response the feedback must reach the user immediately, hence the device must ‘push’ the information to the user. Secondly *all* users in the home must be aware of the feedback, no matter where they are located within the home, as they may each cause the breaker to trip by increasing the load. Hence the feedback must not be a point source of information but rather have a ubiquitous reach. Thirdly, the feedback needs to indicate the current level of power demand, ranging from moderate to extreme. The reason for this is that, even at the moderate level (e.g. just the oven on), the addition of just a single further high power device (e.g. iron) and one medium power device (e.g. fridge) can lead to a trip. Finally, it is important to consider the context in which the feedback will be provided; the target community is low paid, and therefore cost is a constraint on the implementation.

Typically feedback is provided to users visually. A user information [13] unit has been trialled in South Africa where the user interface is a three colour (green, amber red) visual display. The feedback is triggered both by local measurements and by information communicated from a central control room. The drawback of the visual display is that the user is not always facing the information unit, or is perhaps not even in the same room.

Whilst visual displays have the potential to provide detailed information about electricity demand, they are not always located such that they are visible to the consumer at the necessary point in time. As users are often physically occupied with tasks that might increase their energy consumption, such as housework, they are unlikely to pay constant attention to the display. Instead, we propose that an audio cue may offer a superior interface [14] that reaches a greater area of coverage in the house, and provides immediate notification of usage status to the consumer, thus addressing issues one and two. Issue three can be achieved through the use of a range of cues provided via interactive technologies, though care must be taken to ensure that they do not become a nuisance to users [15]. As audio devices are low cost, the final is also solved.

Therefore the authors propose that the most appropriate form of feedback applicable to the specific context of power management (design criterion 1) is that of a suite of audio cues. The next section explores the idea that appropriately designed audio feedback can improve the level of positive responses from the end users. In addition this paper investigates whether different sound symbols can be used to effectively warn end-users about power as well as energy constraint. It also tries to determine if the audio symbols can be used to communicate a sense of the urgency of the problem.

4 Design Parameters for the Use of Audio Cues

For the audio cues to evoke an appropriate response from users they must be readily distinguishable from one another across the various levels of energy usage to which the signals have been allocated. The implemented audio cue set must also be relatively intuitive to respond to, requiring a minimal learning period for users to become accustomed to the scale of intensity contained within the batch of samples. To achieve this, the musical parameters are progressively increased corresponding to an increase in power usage. However, the individual parameters for variation must be carefully identified in order to accommodate both the distinguishability and intuition requirements of the design so as to meet design criterion 2.

When choosing audio parameters to investigate, it is crucial to consider the impact that they might have upon the user once introduced into their domestic environment. The audio samples utilised must induce a sufficient trigger at the critical end of the scale to bring about alterations to user behaviour, yet must also be benign enough to avoid excessive irritation for lower energy usage levels [16]. If the audio cues are too demanding at all energy usage levels, users may be inclined to eliminate the audio functionality of the energy monitors entirely. In order to achieve this aim, the sound samples must increase in urgency, which can be achieved by changing certain properties as the level of energy usage increases.

Although certain elements (such as melody, harmony and rhythm) may be used to impart levels of urgency, they offer consistent irritation levels to users and thus are not appropriate for this application. For example if a major-harmony themed melody is repeated over a sustained period it may impart less urgency than a minor-harmony themed alternative [16]. However, the constantly looping phrase is likely to be equally irritating to the user regardless of the variant, quite possibly resulting in deactivation of the monitoring device entirely. Accordingly, foundational musical elements that can be utilised with simple tones in order to create audio cues that feature high degrees of fundamental variation offer the best building blocks for the sonic elements required for this application.

The pitch (or frequency) of a note is a fundamental musical property that can be varied with profound effect. Whilst some people struggle to recognise subtle fluctuations in tones, most are capable of recognising substantial changes in pitch. As lower pitched tones sit quite subtly amongst background noise and higher pitched tones tend to cut through more noticeably, variations in pitch are an ideal parameter to explore in this domestic context.

Tempo (or speed) is one of the most basic musical devices, variations of which are instantly recognisable. As tempo is entirely independent of pitch, it may be recognised and experienced by even the most 'tone-deaf' and musically-uneducated amongst us. Furthermore, different tempos are easily distinguishable from one another, making tempo a natural element to be exploited in this application. Extremely slow tempos can result in long intervals between sonic elements, reducing the irritation and urgency factor associated with an audio cue. Fast tempos have the opposite effect, and hence tempo is deemed appropriate for further exploration in this work.

Texture is the tactile quality that may be ascribed to a sonic element; an abstract concept that often leads to the use of adjectives such as 'rough', 'smooth', 'round' or 'thin' in order to describe sounds. It is a fundamental building block of music, and is easily distinguishable to the human ear being entirely separate from harmony. Given that the textures of sounds can have effects on listeners that range from 'soothing' to 'jarring', this element is a natural candidate for inclusion here. However as the variations are subtler, it is used in conjunction with changing tempo.

In addition to such musically oriented parameters, we are subjected to a diverse range of audio stimulus that affects our behaviour, such as the hooting of car horns, barking of dogs and so forth. Accordingly, the use of such audio can be implemented in order to generate responses in people that are directly related to generic experiences of the world around us and do not require any level of musical abilities in order to distinguish. This makes the use of non-musical sonic samples, recorded from the surrounding environment worthy of investigation.

Thus the properties of pitch, tempo, texture and real-world association were chosen for evaluation in this application. The sonic samples utilised for the real-world association category of audio cues were selected from within an animal theme, using fairly generic animal sources. The noises selected for use were deemed to be both fairly universal (mainly domestic animals) and to provide a subset of sounds to which the vast majority of users would have been exposed with relatively high frequency during their lifetimes. To see how users would react to the sounds a survey was conducted.

5 Survey Methodology

The purpose of the survey was to determine how the effectiveness of each of the four categories (pitch, tempo, texture and real-world association) in distinguishing between the following five levels of power consumption:

1. Moderate power usage: above average rate of consumption.
2. Moderate-high power usage: significantly above average.
3. High usage: energy consumption should not be increased further
4. Very high power usage: approaching trip level of main breaker, reduce usage as soon as possible.
5. Extreme power usage: about to trip main breaker, immediate action required.

A ten second sound sample was generated for each level. The musical properties of interest were incrementally increased for each sound representing the correspondingly increasing power level.

A set of 15 randomly selected sound samples per category was placed in a video. The first five samples randomly covered all 5 levels. We call this the 'learning stage' as it is the first time the person is exposed to the sounds. The next 10 samples randomly covered each of the 5 levels twice. This latter data is evaluated for consistency and accuracy. As each sample was played, the person was asked to identify which level they thought the sound represented. To avoid bias users were not told how the sounds vary, and the categories were randomly presented to the users.

At the end of the survey, users were then asked two open questions: (1) which category they thought the most effective and (2) at which point they would take action. Anonymous demographic information was also collected.

6 Findings

There were 61 respondents (8 New Zealand, 21 South Africa, 32 UK; 19 female; 34 under the age of 20 and 10 over the age of 50). The mean time to complete the survey was 17 minutes. Three respondents that did not complete the survey were discarded.

6.1 Consistent and Accurate Interpretability

The second criterion is that the feedback cue is interpreted consistently and accurately. Consistency is evaluated using the metric of the percentage of users whose second and third responses to the same sound level were identical, as shown in Fig. 2. Accuracy is represented by the offset between the actual and the perceived level. The metrics used for evaluation are the mean and standard deviations of this offset, Fig. 3.

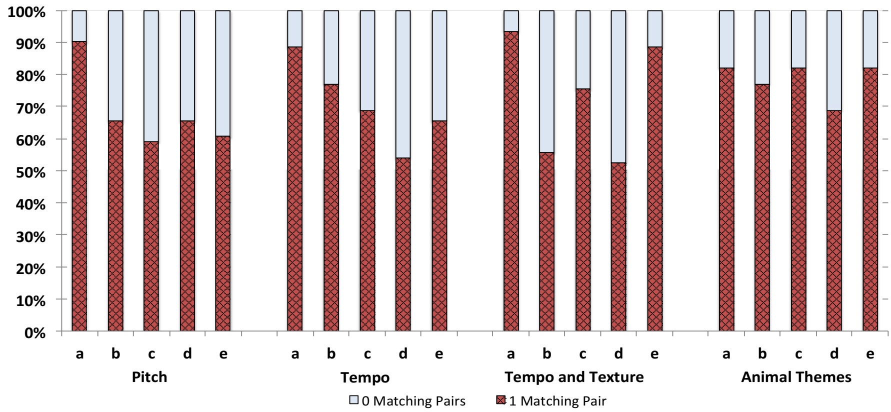
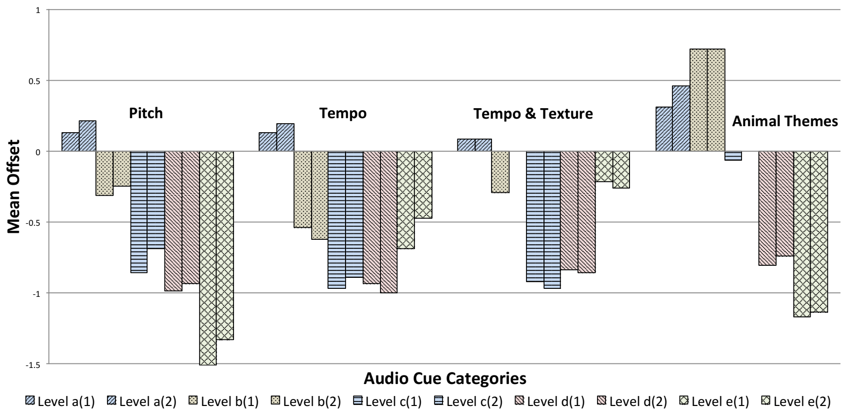


Fig. 2. Consistency of user responses to second and third iterations of each audio cue level

Pitch. Less than 66% of the respondents are consistent in 4 of the 5 levels. The exception is level (a), which has 90% consistency rate. However, it should be noted that the low frequency sample used for this set of audio cues could not be heard clearly on many laptop and cellphone audio-speakers, thus appearing as a change in both volume and pitch, which may explain the high level of consistency. This category had the worst overall results for consistency. The standard deviation and offset plots in Fig. 3 show a distinct worsening of performance as the pitch is increased. At level (e) the offset is greater than -1.5, indicating that on average all the respondents severely underestimated the urgency. This category had the worst overall results for accuracy.

Tempo. This category featured high consistency (> 70%) for the lower levels. However, the performance drops off for the higher energy consumption levels' of (c) – (e). This provides an indication of the existence of a tempo-urgency threshold, beyond which users find all cues to indicate extreme energy usage and thus struggle to make consistent associations. Accordingly some further method of differentiation may be required to make higher tempo sounds more distinguishable from one another.



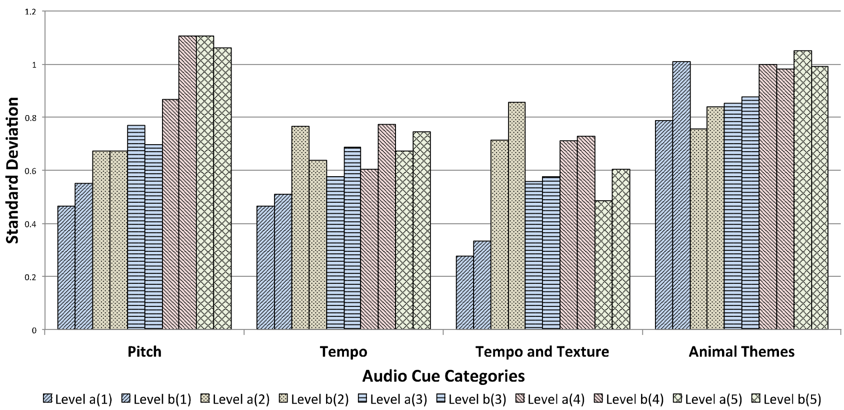


Fig. 3. The mean and standard deviation of the offset between actual and perceived level for second and third instance of each audio cue

The standard deviation and offset plots show that the tempo cues performed better than the pitch cues on both the bottom and top ends of the scale, especially the latter. This indicates that increasing urgency can be imparted via the use of higher tempos, and that they also perform well in the lower range. Given that all of the tones used in this test were of the same pitch, and thus could be reproduced with equal presence through all varieties of audio-speaker, it can be concluded that the use of tempo is likely considerably more effective for expressing lower urgency levels than pitch would be under good sonic conditions.

Tempo and Texture. The introduction of the texture parameter significantly improves the consistency at levels (c) and (e) by 10% and 15% respectively, at the expense of level (b), down by 25%. This suggests that five levels of urgency may not be practical for an audio interface of this nature. Rather, the use of a maximum of three notification levels would likely lead to better results, with users making the correct associations far more easily. This category is the most consistent for the extreme low and high levels. Levels (a) and (e) also show a small offset (<0.25) and a low standard deviation (<0.5). The offset and standard deviation of levels (c) and (d) remain unchanged when adding texture. This category is also the most accurate for the extreme low and high levels.

Animal Themes. This set of audio cues yielded the highest consistent results overall (>70%), indicating that respondents found it easy to make associations between the sounds and energy consumption levels. However, the mean and standard deviation of the offset are the worst of the four categories. These sounds contain significant meaning making them easy to distinguish, but results indicate that each user interprets the sound differently. If similarly complex sounds samples can be found that generate more universal associations within users, then the approach could yield far more accurate results.

6.2 Appropriate Response Timing

The third design criterion states that the feedback should provoke a response at the appropriate point in time. As this test was not conducted in a live setting, users where instead asked at which level they would consider taking action. The results are shown in Fig. 4.

The majority of respondents indicated that they would take physical action to reduce energy consumption around the audio cue level they had perceived to be associated with level (c) usage. Respondents may have interpreted this question to be an assessment of their own commitment to energy reduction, and may thus have chosen a moderate response level that they felt to be the appropriate response. However, the responses tail off in both the high and low directions, providing at least some basic indication that the overall range of urgency covered in the tests is centred around a level where an active user response may be triggered.

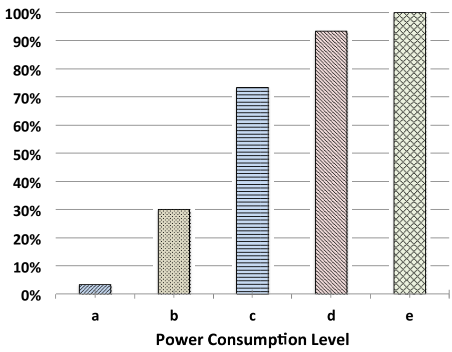


Fig. 4. Cumulative user perception of level at which action should be taken to reduce demand

6.3 User Perceptions

This fourth design criterion states that the feedback should be positively perceived the user. This was assessed by analysing the responses to the question "Please tell us which set of three tests you thought were the most effective and why". Results are shown in Fig.5. This data indicates the users perception of the efficacy of the different categories of audio cues.

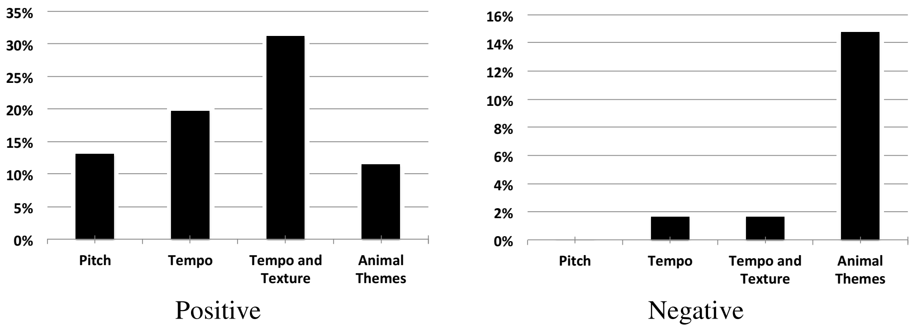


Fig. 5. User perceptions of test effectiveness by audio cue category

The combined tempo and texture category was perceived to be most effective (>30%). This result tallies with the analysis presented in Section 6.1. Respondents deemed the tempo cues to be the next most effective, although considerably less so, receiving 37% less positive feedback than the combined cues. The standalone pitch and animal sound variants of the test were found to be the least effective, receiving 58% and 63% less positive feedback respectively than the combined tempo and texture test.

The overwhelming majority of negative perceptions were aimed towards the animal themed audio cues, users finding them to be either high in annoyance factor or challenging to rank in terms of urgency (again backed up by the numerical analysis).

It should be noted that many respondents acknowledged the tempo element of the tempo and texture audio cues as being a significant contributor to that test's effectiveness. Thus, when considered in combination with the positive feedback recorded for the tempo and texture test, respondents can be considered to have found tempo to be the most effective parameter by a wide margin.

Whilst this study has tested for four specific audio traits, it would be of considerable interest to investigate a wider range of properties, such as rhythm, melody and harmony, as well as testing further cultural associations beyond animal themes. However, these would have to be applied in such a manner that they also featured low irritation indices for lower energy usage levels, perhaps via combined usage with tempo, volume or frequency of performance.

7 Conclusion

This paper addresses the issue of developing a design methodology for providing immediate and intuitive audio feedback about high power consumption, especially during periods when the power level is approaching the capacity of the main circuit breaker.

The four criteria used in this study for the assessment of the efficacy of the feedback mechanism are that: (1) it is appropriate to the specific context in which it is intended to be used; (2) it is interpreted consistently and accurately, (3) it provokes a response at the appropriate point in time, and (4) it is positively perceived by the user.

Due to the specific requirement for an immediate response that is independent of the location of the user, and that multiple levels of feedback are useful, a group of five audio cues were used. Four categories of cues were developed - three based on fundamental musical properties: pitch, tempo and tempo-with-texture, and one based on complex sounds (animal noises).

A survey of 61 respondents showed that the tempo-with-texture category best met the four requirements.

References

1. Paton, C.: Eskom Was 'On the Brink of a Power Shutdown'. Business Day Live (May 20, 2003), `http://www.bdlive.co.za/business/energy/2013/05/20/eskom-was-on-the-brink-of-a-power-shutdown` (retrieved February 1, 2014)
2. Zehir, M.A., Bagriyanik, M.: Demand Side Management by Controlling Refrigerators and its Effects on Consumers. Energy Conversion and Management 64(1), 238–244 (2012)
3. Van Blommestein, K.C., Daim, T.U.: Residential Energy Efficient Device Adoption in South Africa. Sustainable Energy Technologies and Assessments 1(1), 13–27 (2013)
4. Xia, X., Setlhaolo, D., Zhang, J.: Residential Demand Response Strategies for South Africa. In: IEEE Power and Energy Society Conference and Exposition in Africa (PowerAfrica), pp. 1–6. IEEE (2012)
5. Tewari, D., Shah, T.: An Assessment of South African Prepaid Electricity Experiment, Lessons Learned, and Their Policy Implications for Developing Countries. Energy Policy 31(9), 911–927 (2003)

6. CBi-electric Load Control Relay (2014), `http://www.cbi-electric.co.za/products_select.php?p=13#245` (retrieved February 3, 2014)
7. He, H.A., Greenberg, S., Huang, E.M.: One Size Does Not Fit All: Applying the Transtheoretical Model to Energy Feedback Technology Design. In: Proc. CHI 2010, pp. 927–936. ACM Press (2010)
8. Allcott, H., Mullainathan, S.: Behavior and Energy Policy. Science 327(3), 1204–1205 (2010)
9. Ehrhardt-Martinez, K., Donnelly, K.A., Laitner, J.A.: Advanced Metering Initiatives and Residential Feedback Programs: a Meta-Review for Household Electricity-Saving Opportunities. American Council for an Energy-Efficient Economy, Washington (2010)
10. Froehlich, J., Findlater, L., Landay, J.: The Design of Eco-Feedback Technology. In: Proc. CHI 2010, pp. 1999–2008. ACM Press (2010)
11. Fitzpatrick, G., Smith, G.: Technology-Enabled Feedback on Domestic Energy Consumption: Articulating a set of design concerns. IEEE Pervasive Computing 8(1), 37–44 (2009)
12. Ford, R., Karlin, B.: Graphical Displays in Eco-Feedback: A Cognitive Approach. In: Marcus, A. (ed.) DUXU/HCII 2013, Part IV. LNCS, vol. 8015, pp. 486–495. Springer, Heidelberg (2013)
13. Util Labs Low Voltage Smart System (2011), `http://www.utillabs.com/sites/default/files/news-events-downloads/lvss_brochure_final_web_2.pdf` (retrieved February 4, 2014)
14. Walker, B.N.: Consistency of magnitude estimations with conceptual data dimensions used for sonification. Applied Cognitive Psychology 21(5), 579–599 (2007)
15. Fogg, B.J.: A Behavior Model for Persuasive Design. In: Proc. International Conf. on Persuasive Technology, pp. 40–46. ACM Press (2009)
16. Kallinen, K.: Emotional Responses to Single Voice Melodies: Implications for Mobile Ringtones. In: Human-Computer Interaction - Interact, pp. 797–800 (2003)