# Managing Control, Convenience and Autonomy

## A Study of Agent Autonomy in Intelligent Environments

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**Abstract.** There are many arguments for and against the use of autonomous-agents in ambient intelligence and intelligent environments. Some researchers maintain that it is vital to restrict autonomy of agents so that users have complete control over the system; whereas, many others maintain that there is a greater benefit to be gained by employing autonomous-agents to take some of the work load off the user and increase user convenience. Both of these approaches have their distinct advantages but they are not suitable for all since people's opinions and concerns regarding autonomy are highly individual and can differ greatly from person to person. This work explores how it is possible to make intelligent environments more dynamic and personalisable by equipping them with adjustable autonomy, which allows the user to increase or decrease agent autonomy in order to find a comfortable sweet-spot between relinquishing/maintaining control and gaining/losing convenience. This chapter discusses how adjustable autonomy can be achieved in intelligent environments, reports on a recent online survey conducted to gauge people's opinions of different levels of in intelligent environments, and discusses a user study for which an experimental adjustable autonomy enabled intelligent environment was developed. This work aims to raise awareness of the issues with using static (and extreme) levels of autonomy amongst researchers of intelligent environments and ambient intelligent environments.

**Keywords**. adjustable autonomy; mixed-initiative interaction; autonomous agents; intelligent environments; ambient intelligence; pervasive computing;

## Introduction

The use of autonomous-agents in ambient intelligence and intelligent environments has been a much debated topic. Some believe that there is a risk of creating something comparable to Bentham's Panopticon [1] or some notion of 'Big Brother' being able to monitor our every move and know all of our personal interests, as in the famous book Nineteen Eighty-Four by George Orwell [2]. Over the years, literature has seen many authors warning of such dangers, for example [3-6]. Moreover, some researchers believe that delegating tasks to autonomous-agents can take away the sense of

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achievement from users, for example Ben Shneiderman was quoted as saying: "I think users want to have the feeling they did the job – not some magical agent" [7]. Also, as we're told by Callaghan et al., an end-user driven approach to intelligent environment management can encourage creativity in users, it goes beyond the "current DIY approach of paint and wallpaper" and allows people to customise (or decorate) their homes in a digital sense [8]. For reasons such as these, many researchers in intelligent environments take the stance that the use of autonomous-agents should be greatly restricted, and instead the end-user should always be given complete control over all systems. In these end-user driven approaches, it becomes the responsibility of the user to program the intelligent environment in order to create automated behaviours, although the user of the system may not actually have any knowledge of computer programming nor any technical knowledge of the system. An end-user driven approach usually adopts a simplified programming interface to enable the end-user to program the behaviour rules more easily, as in [9-11].

In most situations, producing a system that empowers the user might seem the logical choice; however, problems can arise in an end-user driven system since the intelligence and adaptability of the system depends heavily on the creativity, intelligence, willingness and ability of the user. For example, users may be too busy at times, may have a low level of confidence in their ability to manage such a complex system, or users may even have a physical disability and find it very difficult or even impossible to interact with computer devices. In these situations, autonomous-agents can be very useful as they are designed to operate on the user's behalf and greatly reduce the cognitive load, and sometimes the physical requirements, placed on the user in managing the intelligent environment [12].  In high level terms, autonomous-agent driven intelligent environments employ artificial intelligence and machine learning mechanisms to program automated behaviour in the environment by monitoring  and learning from the user's behaviours and interactions with the environment and system, as in [13, 14].

Pattie Maes is one of the pioneers in the research area of software agents. She believes that agents will become ever more vital as computing systems become increasingly complex: "as computers are used for more tasks and become integrated with more services, users will need help dealing with the information and work overload" [15]. Intelligent environments and ambient intelligence systems are exactly the kind of thing that Maes is talking about here: they contain a myriad of services, devices and applications that all need to be managed. Posland agrees with Maes' argument in his book, Ubiquitous Computing [16]. He points out that "without autonomous systems, the sheer number and variety of tasks in an advanced technological society that require human interaction would overwhelm us and make system operation unimaginable".

While both the end-user driven and autonomous-agent driven approaches have great advantages, they are only suited to certain types of users [17, 39, 40]. This work explores how we can make intelligent environments more dynamic and personalisable by equipping them with adjustable autonomy, and allowing the user to explore the trade-off between the level of convenience offered by autonomous-agents and the amount of control offered by end-user driven systems.

An online survey was recently conducted, which aimed to investigate people's opinions of the use of agent autonomy in intelligent environments [18]. The results show that people have many different concerns when it comes to ambient intelligent systems and their attitudes towards autonomous-agents are highly individual and differ

greatly between people. Furthermore, the results strongly indicate that different people may prefer different levels of autonomy in different situations and for different sub-systems of an intelligent environment, plus their views may drift over time (e.g. as they learn more about consequences of using the technology). As a follow up to the online survey, a working adjustable autonomy intelligent environment has been implemented and a series of user trials were conducted, which aimed to gain deeper insights into the reasoning behind people's attitudes towards different levels of autonomy and explore how using adjustable autonomy can change people's opinions of intelligent environments and ambient intelligent systems.

The next section of this chapter discusses some background and related work including previous approaches to management of intelligent environments and a selection of previous studies relating to user needs and concerns in intelligent environments. Section 2 discusses adjustable autonomy and how it can be applied in intelligent environments. Section 3 describes the Adjustable Autonomy Intelligent Environment (AAIE) architecture model and how it can be used to achieve adjustable autonomy. Section 4 reports on the recent online survey conducted to assess people's opinions of the use of autonomous-agents in intelligent environments. Section 5 describes the experimental set up and discusses the user trials, and Section 6 goes on to compare the findings to the earlier survey. Finally, Section 7 gives a concluding discussion. This work aims to raise awareness of the issues related to using static (and extreme) levels of autonomy amongst researchers of intelligent environments and ambient intelligence systems.

## 1. Background and Related Work

### 1.1. Previous Approaches to Intelligent Environment Management

The majority of research to date has focused on two mainstream approaches to intelligent environment management. Firstly, an end-user driven approach can be taken. In this approach it is the responsibility of the end-user to create and maintain behaviour rules to achieve automation and adaptability in the intelligent environment, although the user of the system may not actually have any knowledge of computer programming nor any technical knowledge of the system. The second approach is to make the system autonomous-agent driven. Here the system makes use of machine learning, pattern recognition and other artificial intelligence techniques to create behaviour rules by learning from the user's behaviours and interactions with the environment in context with the current environmental state and conditions.

There have been many fruitful example of end-user driven intelligent environments in the past. For example, Humble's jigsaw puzzle approach breaks down the intelligent environment into device components (and their corresponding functions) which are each represented by a jigsaw puzzle-like piece that can be 'snapped together' in a chain from left to right to describe the desired functionality of the system [9]. Another example is Pervasive interactive Programming (PiP), developed at the University of Essex [11]. PiP also breaks down the system and allows the user to pick and mix from different functionalities of devices, grouping them together to form virtual pseudo-appliances known as MAps (Meta -Appliances -Applications). PiP uses a programming-by-example approach that allows the user to demonstrate the desired behaviour for any given MAp by interacting with either the physical environment itself

or graphical representations of devices in the environment, thus creating behaviour rules for automation.

Many solid examples of autonomous approaches to intelligent environment management can also be found. Mozer's Adaptive Home uses reinforcement learning and a predictive neural network to control systems such as lighting, heating and ventilation in an attempt to reduce operational costs whilst still maintaining an acceptable level of user comfort. [14]. The iDorm developed at the University of Essex focuses on modelling user activities by employing fuzzy logic mechanisms to generate *If-Then* rules for system behaviour. Rules are generated in a life-long learning mode by continuously monitoring and interpreting the user's interaction with devices with respect to the current state of the environment [13].

End-user driven and autonomous-agent driven approaches can be seen as being at two opposite ends of a scale. An end-user driven approach empowers the user, giving them complete control in managing the system, where as an autonomous-agent driven system disempowers the user handing complete control over to a collection of agents. Many believe that producing a system that empowers the user is the most logical choice. End-user driven approaches not only give the user as much control as possible but also make the system much more transparent to the user, which could greatly reduce any concerns of trust and privacy a user may have. Nevertheless, some users may lack the ability or confidence to program an intelligent environment system, even with a simplified programming interface. In even more extreme cases, users with severe medical conditions or physical disabilities, who are a major target audience for intelligent environments, may find it very difficult or even impossible to interact with computer devices. In these situations an autonomous system is clearly the superior choice; it greatly reduces the cognitive and sometimes the physical load placed on the user in programming and managing the system. The Callaghan-Clarke-Chin (3C) model, shown in Figure 1, is a socio-agent framework that illustrates this concept [8]. Each quadrant represents one extreme type of usage that may be encountered as a system becomes exclusively autonomous or end-user driven given the user has a phobia (fear) or philia (love) of the system. Ideally we wish to avoid misuse and sabotage of the system and maximise creative use and symbiosis between the user and system.

The approaches to intelligent environment management described in this section have all been either entirely end-user driven or entirely autonomous-agent driven and hence maximise either creative use or symbiosis but cannot provide both (with respect
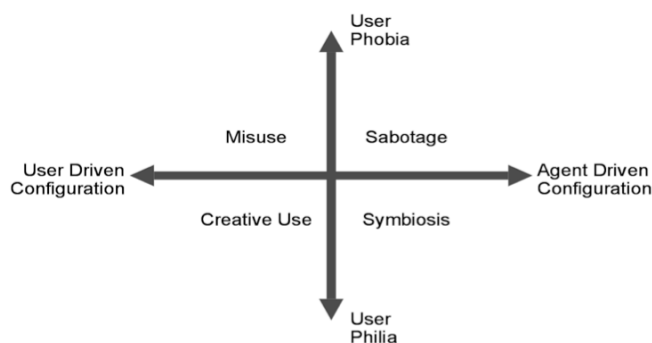


**Figure 1**. The Callaghan-Clarke-Chin (3C) model

to the 3C model). Maximising creative use and empowering the user with an end-user driven system may bring about a user's phobia causing the user to misuse the system, albeit perhaps unintentionally. Conversely, trying to maximise symbiosis by providing an autonomous-agent driven system may also trigger a user's phobia and cause the user to sabotage the operations within the system, again albeit perhaps inadvertently. One can see how user acceptance of intelligent environments and ambient intelligent systems depends greatly on the user's attitudes towards the technology and the concerns brought about by using the technology or having it so deeply embedded in their lives. The next section gives an overview of a selection of recent research that explores user needs and concerns relating to ambient intelligence and pervasive computing.

### 1.2. User Needs and Concerns

Recent research has seen many studies of user requirements and concerns in ambient intelligence and pervasive computing. This section discusses a selection of these studies, which are relevant to this work.

A study by Montano et al. at Göeburg University in Sweden conducted a number of interviews based on scenarios to try to gain a better understanding of people's concerns and requirements for smart homes [19]. Their main findings were that everyday users want support for tedious chores, such as house work, and greater security systems that a smart home might provide, although they are afraid to use complex systems. They found that a critical issue for users is control; in particular, users want to feel free in their homes to be able to execute their own ideas and be confident that everything operates in the way they expect it to. Another significant issue the authors found was that of privacy: users are worried about transmission and storage of their personal data externally.

The Amigo project was a cross-cultural study conducted across six different sites in five European countries [20]. In the project, Röcker et al. aimed to discover the requirements that potential users have in order to accept pervasive technology into their homes. Their findings concurred with Montano et al. They found that people's most paramount concern is maintaining control and responsibility in their homes, and that people expressed fears of lack of privacy and security in a smart home. What's more, they also found that people worry that smart homes may encourage laziness and users may become dependent on the systems, and some had fears that intelligent systems may even come to replace interaction between people. This study also identified some benefits that people think smart homes might entail, such as reducing information overload, preventing household accidents, automation of household chores, energy monitoring and saving, and making staying in touch with others easier.

A collaborative study was conducted in Korea and America by Samsung and the American Institutes for Research (AIR) [21]. Chung et al. explored the relationship between people and networked digital devices in their homes to gain an understanding of the future needs for intelligent environments. They found that users were worried about the compatibility of new and existing technology and people had a desire for technology to fit more harmoniously into their lives. Specifically, better user interfaces, communication methods and centralised entertainment resources were of high interest. Also users wanted to be able to customise technology in their homes. One important finding is that users' information needs change dramatically throughout the day: in the

morning users needed the news, weather, and traffic information before leaving for work, and upon returning, they are more interested to know the status of the home.

The Morphome project was a three-year interdisciplinary study between the University of Tampere and the University of Art and Design Helsinki in Finland [22, 23]. They investigated people's opinions by introducing proactive technology (autonomous systems) into their homes. They aimed to answer the following questions such as "What things are people willing to delegate to proactive technology?" and "What kinds of technical and design issues ought to be taken into account when designing proactive technology?". They concluded that people were happy to delegate ambient services (e.g. lighting) and routine tasks (e.g. an alarm for waking up) to proactive technology (autonomous systems), however, they wanted to keep control of more complicated tasks as they are not always so deterministic, for example the task of going to bed, unlike waking up, is not only dependent on time and commitments but it changes greatly from night to night, it also heavily depends on people's mood, what's on television, what they are doing and many other things. Mäyrä et al. found that, in general, many of the study participants took a disliking to the idea of proactive technologies, as they rely on guesswork and could cause more annoyance than benefit in more complex and critical tasks.

A study by Barkhuus and Dey examined how varying levels of autonomy affects users' sense of control when using mobile phone-based services. They defined three levels of interactivity, each with a different level of system autonomy:

- *Personalisation*: allowing users to configure the functionality of their services.
- *Passive context awareness*: presents the user with new context information as it arises and allows the user to choose to configure the functionality how they desire.
- *Active context awareness*: uses sensed context data to control and configure the functionality autonomously.

Their findings showed that users' sense of control lowered as the autonomy of services increased; however, contrary to their original hypothesis, they found that users still generally preferred the more autonomous solutions, as these provided increased convenience. Barkhuus and Dey point out that similar findings were also noted in studies of how users make use of personalisation options provided in desktop applications and large-scale websites – specifically, the majority of users use the default settings or only personalise a small subset of possible features [24].

A commonality found in all of these studies is that the aspect of maintaining control is a paramount concern for potential users of intelligent environments. Additionally, the issues of adaptability, customisability and transparency of the system were also of great concern to many people as well as privacy of personal information and trust in the system. The studies also found that, in spite of their concerns, people could see the potential benefits of intelligent environments and autonomous systems, such as the convenience of automating mundane tasks, enhanced security systems, monitoring energy usage, etc. These studies have each provided very useful contributions to research in intelligent environments and pervasive computing, and this work aims to build upon their findings by examining people's preferences towards varying levels of autonomy in intelligent environments, and the ability to adjust the level of autonomy in intelligent environments. Some of these previous studies have touched on the subject of autonomy but do not specifically examine multiple levels of autonomy; for example, the Morphome project, described previously, assessed people's

attitudes towards only fully-autonomous systems, which they termed proactive technology, and did not take into account any types of semi-autonomous or end-user driven systems. Although the study by Barkhuus and Dey did compare people's opinions towards multiple levels of autonomy, it was investigating autonomous mobile phone services rather than intelligent environments, which arguably present a set of much more sensitive issues. What's more, Barkhuus and Dey's study did not go as far to assess an adjustable autonomy mechanism.

The next section gives a discussion of adjustable autonomy and considers, in high level terms, how it may be achieved in intelligent environments.

## 2. Adjustable Autonomy

Recent research in both Human-Computer Interaction (HCI) and Artificial Intelligence (AI) has seen numerous debates regarding the use of intelligent agents for automation versus the importance of user control and decision making, which closely mirror the debate of end-user versus autonomous-agent driven intelligent environments [7][25]. Hearst points out an interesting duality between research in the areas of HCI and AI [26]: research in HCI aims to produce effective user interfaces that enable and aid the user in executing intelligent actions [27], whereas, in AI, research considers how we can model the way humans think in order to produce computer systems that can perform intelligent actions [15]. According to Horvitz, the concept of mixed-initiative interaction provides a promising compromise in the autonomy versus user control debate; he suggests that "rather than advocating one approach over the other, a creative integration of direct manipulation and automated services could provide fundamentally new kinds of user experiences, characterised by deeper, more natural collaborations between users and computers" [28]. Horvitz tells us that in taking a mixed-initiative interaction approach we can dramatically enhance HCI by enabling computers to work as assistants or associates in cooperation with the user. Capra et al. view mixed-initiative interaction as being "crucial for fostering an active dialogue between the participants, and its use encourages an interactive approach to problem solving; in particular, it avoids the tendency to seek 'one-shot' solutions, is tolerant of failures, permits changes in focus, and encourages an evolving understanding of the underlying context" [29]. According to Novick and Sutton, mixed-initiative interaction is "one of those things that people think they can recognise when they see it even if they can't define it" and they define initiative to mean "taking the conversational lead" or "driving the task" [42]. If we view a number of agents that are using mixed-initiative interaction to cooperate with a human user in some way, then we could say that if an agent is taking more initiative throughout the interaction then it is performing at a higher level of autonomy.

Bradshaw presents us with an interesting vacuum cleaner analogy to explain this [30]. The most manual (non-autonomous) is a 'plain old' vacuum cleaner. It is directly operated by a person's arm, apart from the ongoing sweeping and sucking action of the motor, every action is taken at the initiative and direction of the user. The opposite, a fully-autonomous vacuum cleaner, would turn itself on, vacuum until it decides it's finished and then retreat back to its storage place to recharge. With this vacuum cleaner no initiative or direction is required from the user; it relies only on the initiative of agents. From this it is easy to imagine an example of a mixed-initiative vacuum cleaner; a vacuum cleaner that requires the user to switch it on, place it in a starting

position and instruct it to start vacuuming. The vacuum cleaner would then autonomously move about the room ensuring every reachable spot gets cleaned and, when finished, return back to its starting position and wait to be turned off. Such a vacuum cleaner relies upon initiative and direction from both the user and agents; it relies on mixed-initiative interaction.

By extension, one can see how by providing a system with different operating modes allowing for various levels of mixed-initiative interaction, an adjustable autonomy system is created. Adjustable autonomy, as described by Bradshaw et al., would allow a system to be "governed at a sweet spot between convenience (i.e. being able to delegate every bit of an actor's work to the system) and comfort (i.e. the desire to not delegate to the system what it can't be trusted to perform adequately)" [31]. Bradshaw et al. describe a general method for adjusting the autonomy of agents that works by [30]:

- *Adjusting permissions:* allowing and disallowing certain actions in the environment
- *Changing obligations:* assigning and withholding tasks to and from the agent
- *Restricting possible actions:* restricting resources to the agent and adjusting the capabilities of the agent thus changing the functionality of the agent

Various examples of successful adjustable autonomy systems can be found in recent research in the fields of robotics and artificial intelligence. For example, Brookshire et al. developed an adjustable autonomy system for a coordinated team of robots that enables human intervention in tasks [32]. Their system uses three robots that aim to place a suspended beam on two separate supports. To adjust the level of autonomy, a human user can take control and teleoperate an individual robot for preassigned tasks to aid the robots if they are struggling or in the situation when the robots believe they are facing failure, in which case they ask the user for help. The authors found that by allowing for adjustable autonomy the human-robot team was more successful than either a fully autonomous robot team or an exclusively teleoperated team.

Goodrich et al. created a single teleoperated robot with adjustable autonomy that traverses an area of terrain [33]. Their method to adjust autonomy in their robot is to alter the inner-workings of its decision process to create different operating modes: fully autonomous, goal-biased autonomy, waypoints and heuristics, and intelligent teleoperation. A similar teleoperated adjustable autonomy robot was produced by Bruemmer et al. in which they restrict the agent's abilities to adjust autonomy [34]. In full autonomy mode, the robot has deliberative capabilities and performs global path planning to select its own routes based on high-level user input such as "search this area". In its shared control mode, the robot performs only local path planning reactively based on its immediately surrounding area and user input is required to guide the robot in general directions. In safe mode, the robot is teleoperated but can refuse to execute user commands if it believes them to be unsafe. Finally, in teleoperation mode, the robot has no ability to control its movements and is under complete control of the user.

The work of Dias et al. focuses on adjustable autonomy for teamwork based systems within which agents and users have a peer-to-peer relationship and team members are not known a priori and are picked up on-the-fly based on their abilities [35]. The authors tested their system with and without adjustable autonomy, and with and without human users acting in the team. The authors concluded that a team of robots operating with adjustable autonomy and with human users performed best. The

users in their experiments could issue both high-granularity (direct instructions) and low-granularity (guidance) commands to the robots depending on what was needed. To adjust autonomy they adopted a form of task sharing in which team members could help others, restricting and extending their functionality where necessary.

More recently, researchers in the fields of pervasive computing and ambient intelligence have started to recognise the advantages accruing from a mixed-initiative approach to managing systems in intelligent environments. For example, researchers at the School of Architecture and Landscape Architecture, University of British Columbia, Vancouver, have identified that a central issue in the operational effectiveness of intelligent buildings is the issue of whether 'intelligence' is derived either implicitly or explicitly from the occupants [39]. Also, researchers at Herriot-Watt University, working on the EU funded PERSIST project, noted that the use of exclusive end-user driven methods were not popular with users owing to the high cognitive load placed on the users and that agent assistance was an advantage. In the case of PERSIST the system runs autonomously but requests assistance from the user when it encounters uncertainty in its decision making process [40].

Thus, it can be seen that taking a dynamic approach to autonomy can provide a more robust system that is more adaptable to different contexts, both very important characteristics of intelligent environments and ambient intelligent systems. What's more, with the extra dynamic of adjustable autonomy in our agents, we can allow for control of the system or specific tasks to flow freely between agents and users; hence, in intelligent environments, we can allow the user to choose how much they wish to control the system and how much trust they are happy to place in the system to operate autonomously on their behalf.

Each of the example adjustable autonomy systems discussed here use some form of restriction to reduce autonomy or augmentation/derestriction to increase autonomy in their systems, as described by Bradshaw et al. [30]. In the realms of intelligent environments, applying similar restrictions and augmentations is also possible: we can alter levels of agent functionality, the permissions of agents, or the resources available to them. Thinking in very high levels terms about an agent's operation in an intelligent environment, it can be abstracted down to three major functions: sensing in the

**Table 1.** Examples of how agent autonomy might be changed in an intelligent environment system.

| Agent Function | How autonomy could be altered |
| --- | --- |
| Sensing | By restricting the sensors available to the agent, we can restrict the agent's ability to learn or make decisions on what actions to perform and when, thus greatly reducing the initiative that it provides in the system and hence greatly lowering its autonomy. In doing this it then becomes the task of the user to manage the intelligent environment with no assistance from the agent. |
| Decision Making | The decision making process of the agent can be restricted simply by giving the user a final say on the agent's decisions. For example, if an agent decides that when the bathroom is occupied the lights should turn on, then before agent programs the rule into the system the user is given the chance to accept or reject the agent's decision. Here, the agent's autonomy is reduced by empowering the user to add some initiative into the decision making process. |
| Acting | Similarly to sensing, we could restrict which devices an agent is allowed to perform actions with, which directly alters the overall affect an agent has in an intelligent environment. Here the agent's autonomy is reduced by lowering the number of devices that it can control, and hence the user gains complete control of these devices instead. |

environment; decision making, which usually takes the form of a learning or decision making task; and performing actions in the environment. In each of these major functions, an agent can be restricted and the user empowered in some way to form a mixed-initiative interaction, and hence different levels of autonomy. Table 1 shows an example of how this might be achieved for each of these abstract agent functions.

These are just a few high-level examples of how an agent's autonomy could be changed in an intelligent environment and many more methods surely exist. Section 3 describes the Adjustable Autonomy Intelligent Environment architecture model that has been designed to enable adjustable autonomy in intelligent environments using a confidence-based mechanism for restricting how behaviour rules and automation are created in the system.

### 3. The Adjustable Autonomy Intelligent Environment (AAIE) Model

The Adjustable Autonomy Intelligent Environment (AAIE) architecture model has been designed to enable adjustable autonomy in intelligent environment management. The AAIE model takes the form of an event driven multi-agent architecture and is based around the framework of the University of Essex iSpace [8]. The iSpace, show in Figures 2(a) and 2(b), is a purpose built test bed for intelligent environment and ambient intelligence systems. As well as everything one might expect to find in any other two-bed apartment, the iSpace is also equipped with a multitude of networked sensors and actuators, e.g. internal and external temperature and lighting sensors, real-time location tracking, computer-controllable heating and lighting, and electronically controlled curtains and doors. Built with cavity walls and ceilings containing power and network outlets, it allows researchers to deploy their experimental systems for testing on real human users in an unobtrusive way. All services and devices in the iSpace are networked and controlled electronically wherever possible using an underlying Universal Plug & Play (UPnP) based architecture, making them easily accessible to experimental systems. In Figure 3, the overall architecture of our AAIE model can be seen. In the system we have: the physical environment, which contains numerous devices, sensors and actuators; a Context Agent (CA); an Acting Agent (AA); an Interface Agent (IA); and an Adjustable-autonomy Behaviour-Based Agent (ABBA). The CA monitors the current state of the intelligent environment by



(a) Living room                    (b) Kitchen

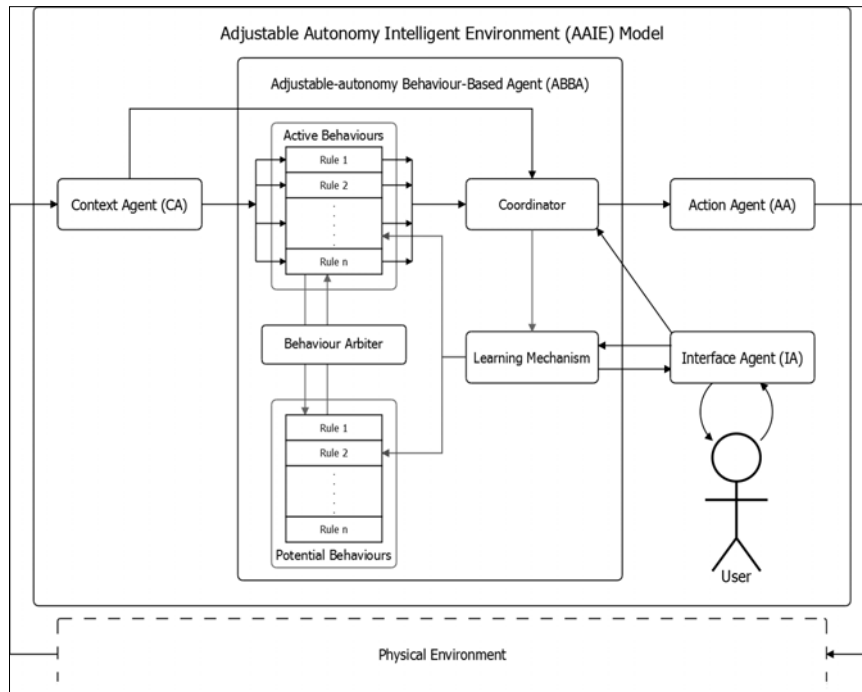**Figure 2**. The living room and kitchen of the University of Essex iSpace.

**Figure 3**. The Adjustable Autonomy Intelligent Environment (AAIE) architecture model.

communicating with the physical environment via UPnP, listening for events and maintaining up-to-date sensor readings. When an event is detected by the CA (i.e. there is a significant change in the state of the environment) the new environment state and event information are passed to ABBA and used to decide on actions to perform in the environment or learn new rules. The AA drives actuators and devices in the physical environment as instructed by the Coordinator of ABBA. The IA provides an interface between the system and the user; it allows this user to directly control devices in the physical environment using a GUI interface and use the rule generating tools/procedures made available by ABBA.

ABBA provides the controlling and learning ability in the system. It is inspired by another management system for intelligent environments, the incremental synchronous learning (ISL) agent developed by Hagras et al. [36]. The ABBA architecture takes the general form of a behaviour-based architecture, as pioneered by Brooks at MIT [37]. In such architectures, a number of agent behaviours (known as behaviour rules in our system) run in parallel and a controller (named coordinator in our system) is employed to coordinate the behaviours or their given outputs into one single output to achieve the desired agent functionality. As seen in Figure 3, the ABBA architecture contains the following components: the coordinator, the learning component, two sets of behaviour rules and the behaviour arbiter.

In the behaviour rule sets, a behaviour rule (r) is defined as a set of antecedents (A) and a set of consequents (C):

$$r = \{A, C\} \Rightarrow \textbf{IF } A \textbf{ THEN } C$$

$$\text{where } A = \{a_0, a_1, ...., a_x\} \text{ and } C = \{c_0, c_1, ...., c_x\}$$

For example:

$$r = \{ \{TempIsHot, AirConIsOff\}, \{TurnOnAirCon\} \}$$

i.e.

$$r = \textbf{IF } TempIsHot \textbf{ AND } AirConIsOff \textbf{ THEN } TurnOnAirCon$$

Behaviour rules may be either generated by ABBA or programmed by the end-user. Each rule is also assigned with a confidence level when it is created: a value between 0 and 1, based on whether it is was created by ABBA or the end-user and in accordance with the selected autonomy level (this is explained in more detail later). A rule can only have an effect on the environment if it is active and can only be active if it has a high enough confidence level. Rules with a low confidence can only be potential behaviour rules and cannot effect the environment. All behaviour rules are visible to all components of the agent. The behaviour arbiter component regulates the behaviour rules. The confidence of all rules slowly degrades overtime, and if an active rule's confidence level drops below a certain threshold then it is dropped down into the potential set and if a potential rule's confidence level drops below a very low threshold (zero for example) then it is deleted. This confidence degradation reduces the chance that the agent's memory will become full. To adhere to the "User is King" clause, created by Callaghan et al. [12], a user programmed rule will always have a confidence level of 1, which does not degrade over time, and a user may always program behaviour rules regardless of level of autonomy.

When an event is detected by the CA (i.e. there is a significant change in the state of the environment or a user action) the new environment state and event information are used as an input to the active behaviour rules and also passed to the coordinator. The active behaviour rules, running in parallel, then produce an output based on the input data if possible. The coordinator regulates/merges the output of all the active behaviours into one single output so that each behaviour rule effects the external environment to an appropriate degree. Additionally, when an active behaviour rule affects the environment the coordinator increases the level of confidence of that rule, where the amount increased depends on the degree the rule is effecting the environment. Thus, the more a rule is used and the more it effects the environment, the less chance it will have of dropping into the potential set and ceasing to be active.

If no behaviour rule produces an output for any given event, then the event information is sent to the ABBA's learning component. If this event is a user action, then the learning component uses the event information to generate a new rule, which is assigned a very low level of confidence (for example 0.1) and is placed in to the potential rule set. If the same user action is observed subsequent times, the confidence of the newly generated rule is raised by a certain amount (incremented by 0.1 for example). A clustering algorithm and genetic algorithm (GA) is used to find similar behaviour rules (i.e. rules derived from similar user behaviour) and merge them together to find (more optimal) new behaviour rules. If a more optimal set of behaviour rules can be found in this way, the confidence of the new rules is increased over that of

the original (merged) rules, and if the confidence level is then high enough, the rule may become active.

To achieve different levels of autonomy in ABBA, we can alter how behaviour rules are generated in the system and change how the confidence level of rules is assigned and increased, which in turn defines how they become active in the system. For example, let us say that for a rule to become active in the system it requires a confidence level of 0.9. Then in a fully autonomous-agent driven system, the agent can learn new rules using the GA and can assign anything up to a confidence level of 1 to rules (i.e. no direct interaction between the agent and the user is required). In a fully end-user driven system however, the agent is restricted so that it cannot learn new rules and cannot assign confidence to existing rules; hence, it is the sole responsibility of the user to manage the system and the agent has no effect. To create a semi-autonomous management style (with high autonomy), an agent could be restricted so that it can generate new rules but can only assign a confidence level up to a cap of 0.75, for example. Once this cap is hit, the agent must then communicate with the user to confirm the rule in order to attain the extra 0.15 confidence required for the rule to become active. Here, since the system requires some initiative from the user, we can say that the agent is no longer fully-autonomous (similarly to the decision making example described in Table 1). For a semi-autonomous management style with low autonomy, the agent could be allowed to create new rules but not to assign confidence to the rules; instead the agent uses its known rules as an experience bank to form suggestions and use these (upon request) to aid the user in programming their desired rules. Here, the user has the majority of influence over rule and the agent can only provide initiative only when requested, meaning that the agent has a lower level of autonomy.

By enabling adjustable autonomy in an intelligent environment we can allow the user to change how much control they give to agents and how much control they wish to take on themselves depending on their attitudes towards the system, devices and agents. The next section discusses an online survey conducted to investigate these attitudes and explore how people might use adjustable autonomy.

## 4. Online Survey

An online survey was developed to gauge people's opinions of the usage of autonomy in smart homes and intelligent environments[3]. This section reports on the results obtained from the survey.

The focus of the survey questions revolved around how much agent autonomy people would prefer to be used in management of a smart home. By management we mean the creation of behaviour rules that describe the automation of services and devices in the environment. Along with the survey an animated video, shown in Figure 4, was produced to enable the survey participants to better understand the survey questions. The video explains the concepts of intelligent environments and intelligent agents, as well as four different management styles (at different levels of autonomy) for intelligent environments:

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[3] A copy of the survey questions and the survey video can be viewed at the following web address: http://ieg.essex.ac.uk/?page_id=957

**Figure 4**. Screenshot of an animated video to explain the concepts in our online survey.

- *Full autonomy*: the agent monitors the environment, learns the user's behaviour and programs rules accordingly.
- *High autonomy*: the agent monitors the environment, learns the user's behaviour and generates rules accordingly but the rules can only become active in the system when they have been confirmed by the user. The user is presented with the opportunity to accept, reject or edit rules at the confirmation stage.
- *Low autonomy*: the user programs the rules using a GUI, in which they build rules using a jigsaw puzzle metaphor. An agent can give suggestions for rules to aid the user.
- *No autonomy*: the user programs the rules using a GUI, in which they build rules using a jigsaw puzzle metaphor.

Over a period of three months, the survey received 159 responses in total. The survey was open to the all above the age of 16. Before the general release and advertisement of the survey, it was piloted on a small number of people from different age groups, backgrounds, technical abilities and some non-native English speakers. This was to ensure that the survey and video were easy to understand and complete. Also, in accordance with the normal practices of survey research, all questions in the survey (and the survey video) were carefully designed not to influence respondent's answers. The survey was advertised via email within the University of Essex, amongst various Google Groups mailing lists (including computer science related groups and general advertisement groups), and to personal contacts via email and Facebook.

*4.1. Demographic Results*

The initial survey questions were designed to attain some demographical information about the respondents. This subsection gives an overview of the results. 63% of respondents were male, 35% were female and 2% preferred not to say. 40% of respondents were aged 16-25, 28% were aged 26-35, 11% were aged 36-45, 8% were 46-55, 10% were 56-65, and 3% 66 and over. 70% of respondents held either an Undergraduate or Postgraduate university qualification and 27% have achieved an A-

Level, GCSE or other qualification, while 3% of respondents preferred not to say. The respondents had a wide range of occupations, such as: Student, Marketing Manager, Receptionist, Building Contractor, House-husband, and Trainee Teacher.

The majority of respondents were heavy computer uses, 70% reported that they use a personal computer (PC) either 31-40 hours or 41+ hours per week. 22% use a computer either 11-20 hours or 21-30 hours per week and only 8% use a computer 10 or less hours per week. 43% of respondents reported they have very little or no experience of computer programming whereas 56% of respondents reported they have some or a lot of computer programming experience, and 1% reported they were not sure. 78% of respondents had heard of a smart home or intelligent environment before taking part of the survey or watching the accompanying video, whereas 19% had not and 3% of respondents were not sure.

Being an online survey, based at a University, it is clear that the respondents may be biased towards educated users conversant with computers. However, we believe this demographic to be representative of a potential audience for the uptake of the type of pervasive computing technology involved: the majority are aged 16-35, regularly use computers, well-educated and are from a variety of backgrounds and occupations.

### 4.2. Survey Findings

As mentioned previously, the main survey questions were designed to gauge people's opinions of how they view the usage of intelligent and autonomous agents in smart homes and assess how they might like to manage a smart home if they were to occupy one.

Figure 5 shows the answers to the first set of questions, trying to determine how useful the survey respondents perceive the different levels of autonomy to be. The respondents were asked to rate each level of autonomy (described previously) on a five-point scale of: not useful at all, somewhat useful, undecided, useful or very useful[4]. As can be seen from Figure 5, the majority for each of the levels of autonomy is either useful or very useful. The fully-end user driven (no autonomy) level seems to be perceived as more useful, with over 80% of respondents saying they believe it would be useful or very useful. For both semi-autonomous management styles (high and low autonomy), around 70% of respondents said they believe them to be either useful or very useful; although the low autonomy level was the favoured of these with 38% of respondents selecting very useful compared to the high autonomy level with only 22% selecting very useful. The full autonomy level seemed to be the least popular with around 60% of respondents saying they believe it to be useful or very useful. Also, only the full autonomy level had a significant number of people, 30%, who answered either not useful at all or somewhat useful. This perhaps indicates a low level of confidence in the ability of agents or even a fear/distrust of intelligent and autonomous agents which may be a very significant finding for the intelligent environment and ambient intelligence research communities. Another interesting point is that for both the high and low autonomy levels, around 10% of respondents were undecided about their usefulness, whereas for the full autonomy and no autonomy levels, only 6% and

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[4] Respondents could also choose not to answer the question. The number of respondents who gave no answer has been omitted from the results for each question. However, by way of providing some insight to this, for the questions regarding fully-autonomous style and both semi-autonomous styles, seven participants gave no answer and for the question about the fully end-user driven styles, nine participants gave no answer.
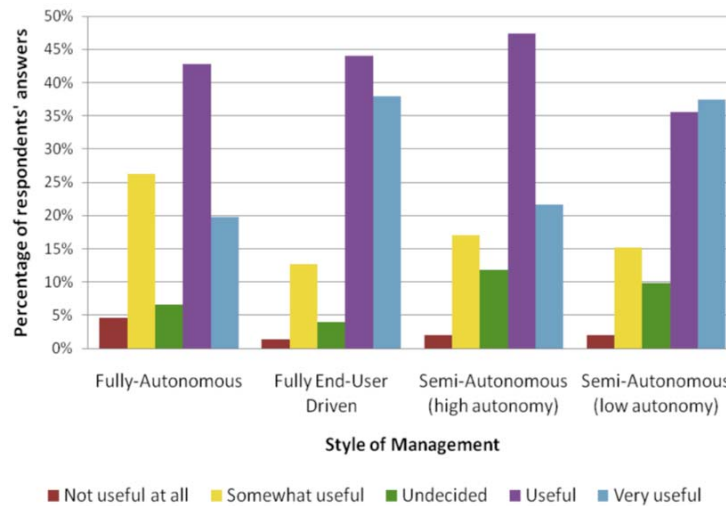
**Figure 5**. Graph showing perceived usefulness of the different management styles.

4% of respondents said they were undecided respectively. Without further evidence, we can only speculate on the reasons behind these results, which could be for example, unfamiliarity with interacting with intelligent systems, not fully understanding the numerous technical issues involved, concerns of trust or even a more deep-seated psychological fears of systems that come close to offering capabilities we regard as the essence of being human, etc. Each of these would be in line with the findings of previous studies of user needs and concerns, as described in Section 1, and also can be seen in the findings obtained in the user trials explained in Section 5.1.

Figure 6 shows the results to the question[5]: *If you were living in a smart home, how useful would you find the ability to change between the different styles of management, rather than always using the same style of management?* As can be seen, the vast majority of respondents think that the ability to change the level of autonomy at different times is either useful or very useful and only one respondent said they think it is not useful at all. The respondents were also encouraged to give a reason for their answer. Some of these include: "very useful - *different tasks require different styles of management*"; "very useful - *It is quite sensible to take the control sometimes while some important decisions will be made, or for a supervisory session while teaching the agent how to act according to a specific situation*"; "useful - *Flexibility to cope with changing circumstances*". The results discussed above support the need for an adjustable autonomy based solution to intelligent environment management. They indicate that while the survey respondents, as potential users of intelligent environments, may prefer the concepts of end-user driven management styles (no autonomy), they also have some interest in the semi-autonomous and full autonomy solutions. What's more, we can clearly see that the survey respondents deem the ability to adjust the autonomy level would be a very useful in an intelligent environment. In the reasons the respondents gave for their answers we can see some interesting trends.

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[5] Seven of the survey participants did not give an answer for this question, which has been omitted from the results forming the results.
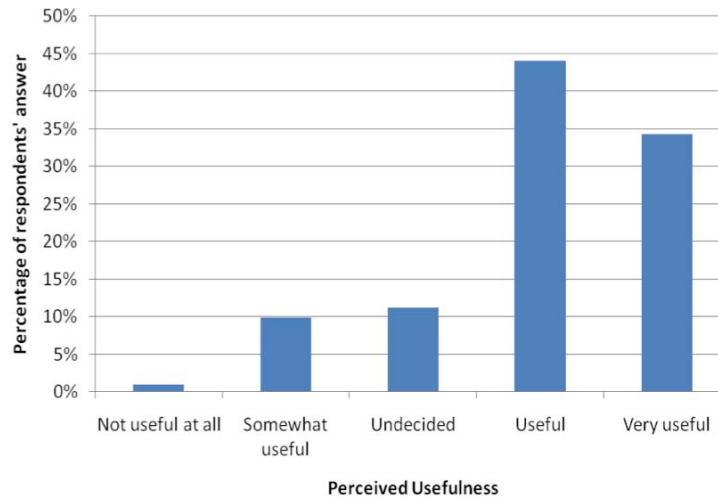
**Figure 6**. Graph showing usefulness of ability to change between the different management styles.

While many stated that they simply desired the extra flexibility, for example "*I would find it very useful as I would not like to be limited to just one way of managing my home, my preferences and needs would change daily and I would like to know that I could have as many options as possible*", many others expressed concerns over trusting an agent, some doubting its ability, worried about it causing annoyance, and some wishing to build confidence in the intelligent agents before giving them too much autonomy, for example "[*I'm*] *worried that agent might do things I don't want or know about*" and "*I would need to build my confidence in an intelligent agent*".

In the next set of questions, the respondents were asked to think about a number of different sub-systems in a smart home and decide at which level of autonomy they would like them to be managed. The different sub-systems were:

- Lighting systems (e.g. automatic room lighting)
- Heating systems (e.g. automatic indoor heating)
- Entertainment and media systems (e.g. recording favourite TV shows, finding news stories, music or movies that might be interesting to you)
- Security systems (e.g. automatically closing and locking doors and windows when the home is unoccupied)
- Environmental services (e.g. monitoring and regulating energy usage within the home)

In each question, the participants were asked to consider how they would like one sub-system to be controlled. Figures 7(a to e) show the percentage of answers attained for each level of autonomy for each individual sub-system[6]. As can be seen from Figures 7(a to e), in general terms, the high autonomy and low autonomy levels were most popular, with the high level being preferred, and the full autonomy level proved

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[6] For all of these questions, seven respondents gave no answer. Again these non-responses have been omitted from the results.

(a) Lighting

(b) Heating

(c) Entertainment

(d) Environmental

(d) Security

■ No autonomy ■ Low autonomy ■ High autonomy ■ Full autonomy ■ Don't know
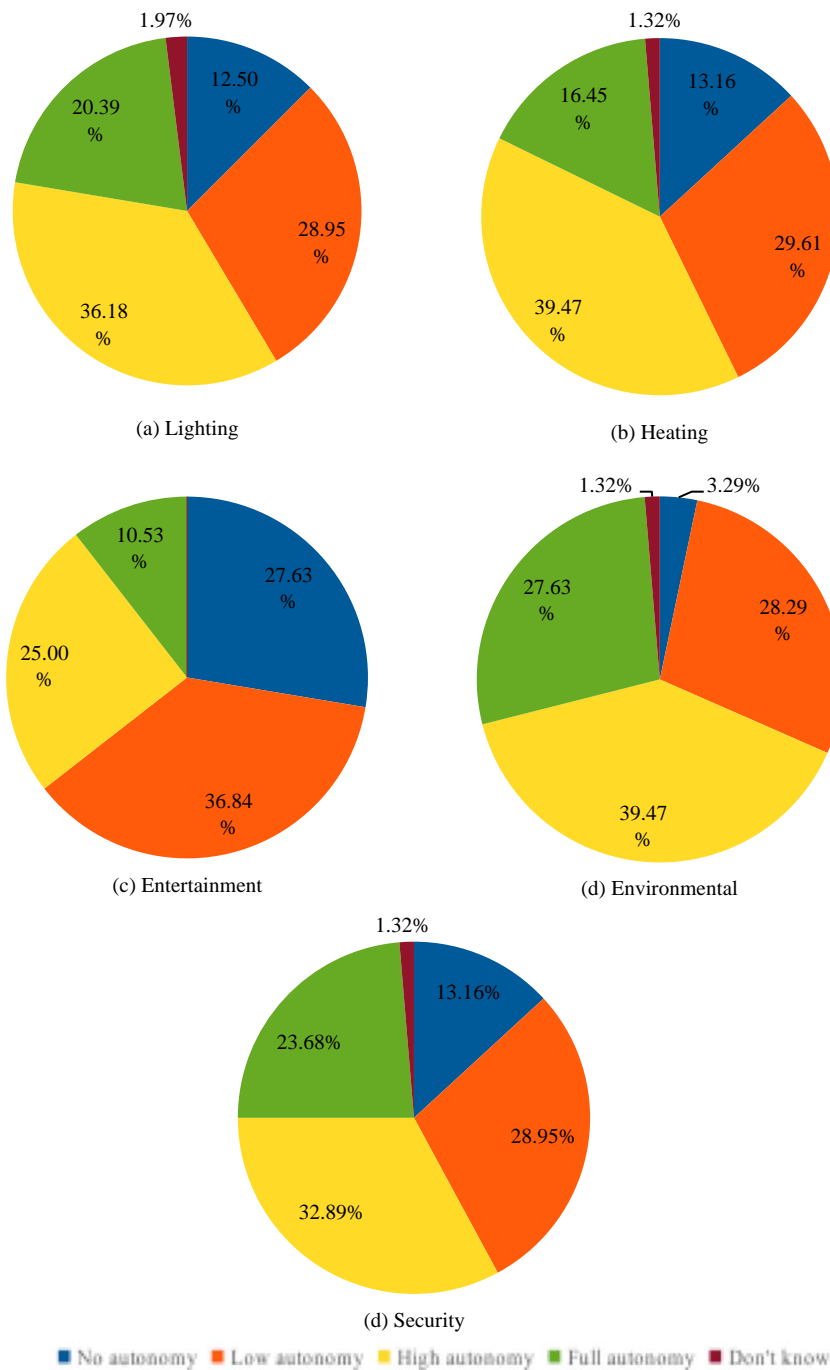
**Figure 7**. Pie charts showing percentage of participants that selected each autonomy level for he respective devices.

more popular than the no autonomy level. This provides an interesting contrast to the results from the previous questions, which indicated that people perceive the less-autonomous management styles to be more useful, with the fully end-user driven no autonomy option proving most popular; however, in these results, when people were asked to think more in depth about what will actually be managed in the intelligent environment, they seem to prefer a higher level of autonomy, with the no autonomy option actually proving to be least popular. Whilst there were some paradoxes in these results, there were also some strikingly consistent findings. For example, heating, which is already semi-automated in most homes, retained this user-preference and for entertainment, which is connected to deep-rooted internal values and tastes, the no autonomy level was a clear winner. As before, without further evidence we can only speculate on the reasons; however, based on the open-ended comments made by the respondents and findings from previous user studies (described in Section 1), one cause of this flip in opinion could be the survey participants' unfamiliarity with the technology, meaning that the task of managing such a complex system might seem daunting for an average computer user. So initially people may prefer the help of an agent to manage the intelligent environment, but over time, as people because more accustomed to the technology, they may refer back to their previous opinion that using a fully end-user driven style of management is better for them.

Another striking and important finding is that people have very different autonomy needs for different types of sub-system. As can be seen in Figure 7, the responses for lighting, heating and security sub-systems were quite similar with the semi-autonomous management styles (high and low autonomy) being preferred and the high autonomy option being favoured; whereas, the responses for the entertainment sub-system tended more towards low and no autonomy, and for the environmental sub-system the results were more evenly distributed between the full, high and low autonomy levels (with a preference towards high autonomy). A possible explanation for this is, for example, lighting, heating and environmental systems could be viewed as non-critical systems (i.e. it doesn't matter too much if they fail) and hence users feel if they were managed autonomously by agents the potential benefit of increased convenience to the user outweighs the potential risk factor of handing over control to intelligent agents. However, as discussed earlier, an entertainment sub-system could be seen as highly personal to the user (connected to deep-rooted internal values and tastes) and something for which the user's preferences could often change depending on mood, time of day, current activity or any number of factors; hence, it could be the case that the survey respondents don't have confidence in the ability of the agent to learn such preferences using only simple environment sensors, and so they believe that the risk of the agent making mistakes, and perhaps causing the user annoyance, outweighs the potential convenience gained by agents managing the sub-system. Put another way, one could argue the question - what is the sense in trying to make an agent learn something it can only partly know and thus make bad guesses at, when that knowledge is known with certainty within the user and can be better extracted by other means, i.e. the user having complete control?

For the security sub-system, the responses were quite mixed but the high and full autonomy levels seemed to be favoured. Although the responses for the security system were similar to those for lighting and heating, most would agree that security systems are much more sensitive to errors; for example, in a smart home one wouldn't want doors and windows to unlock unexpectedly or allow entry to unauthorised people. Contrary to what was shown by the survey results, one might expect that people prefer

to maintain more control over such sensitive system. It may be the case that higher autonomy is favoured here because people are already quite familiar with electronic security systems and automated monitoring, and so autonomous-agent management is seen as being in keeping with how their current security systems already operate and in which they trust. There is a strong indication here that the answers may be dependent on the differing understanding and interpretations of the respondents, which is likely to have been affected by their previous experience with similar systems and technology.

From these results, in general terms, we can see that people prefer the full and high autonomy styles for sub-systems that are not connected to style or taste (e.g. lights and heating), but for systems that are (e.g. entertainment) they prefer low or no autonomy. This further justifies the need for adjustable autonomy in intelligent environment management, as there is no single (fixed autonomy) solution that would be ideal for all users for all parts of their intelligent environment systems. This point is emphasised in the final question of the survey. The survey respondents were asked: *If you were living in a smart home, how useful would you find the ability to choose the style of management [level of autonomy] for individual parts of the system, rather than one setting for the entire system?* Figure 8 shows the responses to this question[7]. As you can see from the graph, the vast majority (over 80%) said they would find this ability either useful or very useful and very few respondents thought that it was not useful as all. Again, the survey respondents were asked to give a reason for their answer. Whilst these answers give a qualitative (and individual) rather than quantitative insight, they do provide a useful feel for what some respondents thought. For example, some respondents answered: "very useful - *As I got used to a smart home I might have more confidence in some things being managed by an intelligent agent before others.*"; "very useful - *There are some things that I'd be happier to monitor myself (security) as a glitch in the system would be very detrimental. There are others that I'd be happy to let run without me having to do anything like the lights*"; "useful - *I'm moody and would like the choice of choosing different management styles as I'd like to have more control over certain things*".

The results from the final question confirm our findings from the previous results. They show that a large percentage of respondents would like the ability to adjust autonomy of individual sub-systems in their intelligent environment. What's more, from the reasons people gave for their answers we gain an interesting insight into people's perceptions of intelligent environments. Many people expressed concerns over privacy of certain sub-systems or did not believe in the ability of an intelligent agent to find effective behaviour rules for the more personal sub-systems. Moreover, others expressed a lack of confidence in their own ability to manage the intelligent environment and said they would dial-down the level of autonomy as their confidence increases.

*4.3. Survey Results Summary*

In this survey we have asked a large number of potential intelligent environments users their opinions on agent autonomy in intelligent environments. From these results, the usefulness for an adjustable autonomy management system for intelligent environments is clear. We can see that different people prefer different levels of autonomy and many

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[7] In this question, thirteen respondents gave no answer. Again these non-responses have been omitted from the results.
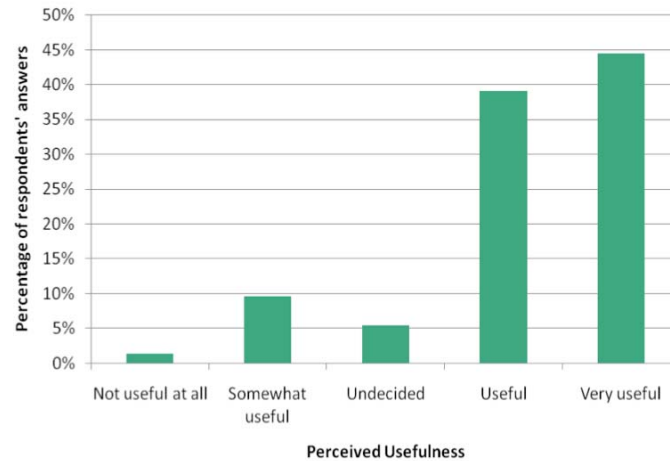
**Figure 8**. Graph showing the usefulness of being able to choose the style of management for individual parts of the system.

people would not always like to use the same static level of autonomy for all sub-parts of the intelligent environment system. For example, we see in the results that people would prefer to maintain a higher level of control (lower level of agent autonomy) for a more personal system such as entertainment and media services; whereas for other sub-systems, such as heating and lighting, people don't mind giving up a certain amount of control in exchange for increased convenience (a higher level of agent autonomy). Additionally, some people feel that, with such a complex system, they would initially prefer a higher level of autonomy, with an intelligent agent taking a role in helping to manage the system, and decrease the autonomy level overtime as they become more accustomed to the technology. We speculate that a person's views may also change over their life, as previous research have reported that older, or medially infirmed people, are comfortable to give up more control as their physical or cognitive ability degrades [41]. Whilst the focus of this survey is different to earlier surveys, as described in Section 1, its results broadly align with them in reporting that people cite control over the system as being their most important concern, and also trust being another issue raised repeatedly throughout the survey.

Furthermore, these findings reveal the value of an adjustable autonomy system, not only for use in real-life applications, but also as a design tool. In the first set of questions, the survey participants showed a preference towards fully end-user driven (no autonomy) management; whereas in the second set, when people were asked to think about managing the individual sub-systems in the intelligent environment, the no autonomy level was the least popular and high autonomy was the favourite. This change in preference here indicates the instability of people's opinions about pervasive technology and in fact their opinions could easily change again once they have experienced a real intelligent environment. Hence, a follow up study has been conducted that gives the participants a chance to interact with an adjustable autonomy intelligent environment. It aimed to gain a deeper understanding of the results obtain in this online survey. The next section details this study.

## 5. User-Based Trials

In order to conduct a follow up study to the online survey, the AAIE model was implemented and deployed in the University of Essex iSpace [8]. The aim of this study was to further the findings from the online survey by gaining a deeper understanding of people's opinions and concerns regarding the use of autonomous-agents in intelligent environments and the reasons behind their opinions and concerns. A total of twenty participants were invited to perform an experiment using the adjustable autonomy system and give feedback on their experiences. The experiments were designed to give the participants a 'taste' of what life living in an intelligent environment might be like. The experiments consisted of three short trials, which asked the user to either perform actions in the environment to allow an agent to learn behaviour rules, for them to create behaviour rules themselves or a mixture of both, depending on the level of autonomy chosen by the participant. The trials were inspired by a generalised view of people's day-to-day routines and activities.

The experiments were carried out in a single area of the iSpace, an open plan living room and kitchen. The devices used in the experiment where dimmable ceiling lights, an air conditioning unit, curtains, and a television. To sense the state of the room, the system was equipped with light level sensors, temperature sensors and a location tracking system. The AAIE system was run on a centralised server and communicated with devices and sensors over a wired network using a UPnP framework.

The experiment participants interacted with the system using a web-based graphical user interface (GUI) via an Apple iPad, which connected to the central server via a wireless network. The GUI was made up of the Rule Creator, Rule Viewer, Autonomy Settings screen and Room Control. The Rule Creator allowed the participant to create new rules. The Rule Viewer allowed the participant to view, edit and delete active rules in the system. Through the Autonomy Settings screen the participant could select an individual level of autonomy for each type of device. The participants could directly perform actions with the devices using the Room Control. The GUI home screen is shown in Figure 9(a) and the Autonomy Settings screen is shown in Figure 9(b) as seen on the Apple iPad.

For the user to create rules in the system, a GUI rule creator was provided. The rule creator was based on a multi-level menu system that allowed a user to build IF – THEN rules using (near) natural language. An example of this can be seen in Figure 10. It shows the user creating an antecedent for the rule (the condition that the user should be in the kitchen in this example) by clicking through the menus to select the state they desire. As the user clicks through the menus (previous clicks are shown by a red dot superimposed on Figure 10), the text-based rule is generated for them, as shown in the preview on the right side of the figure; hence, if the user clicks on "IS In The Kitchen" next then this will also be added to the rule. The same style of menu system is also used by the user to generate the consequent of the rule. The user is able to add multiple antecedents and consequents to the rule, which are added to the rule using the logical AND operator. The user is also able to delete antecedents and consequents if needed.

Throughout the experiment, the participants could choose to create behaviour rules at four different levels of autonomy, similar to those assessed in the online survey. The participant was able to change the level of autonomy for each device at any time during the experiment. The different levels of autonomy, described below, define how much
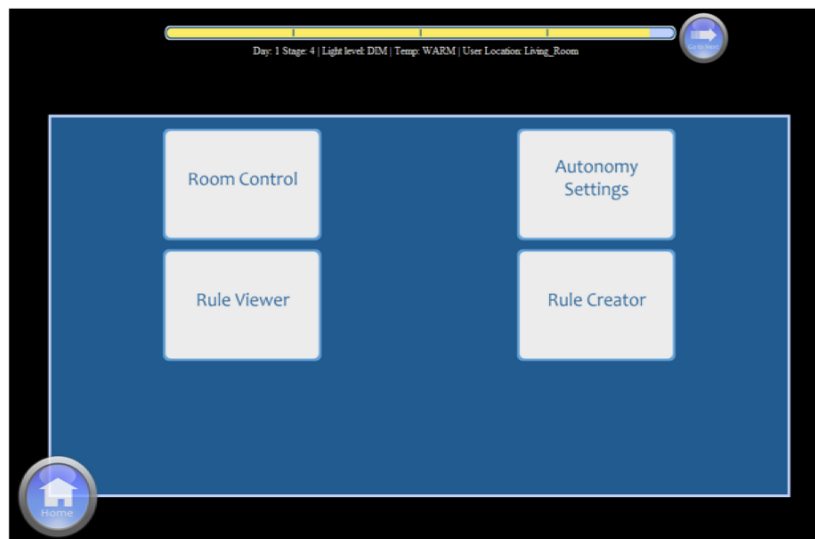
(a) GUI home screen
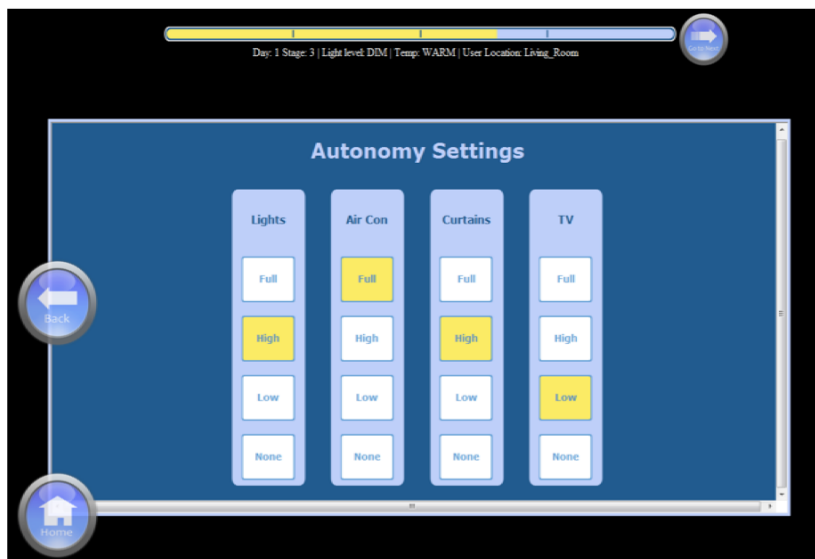


(b) Autonomy settings screen

**Figure 9**. The GUI home screen and the Autonomy Settings screen as seen on the Apple iPad.
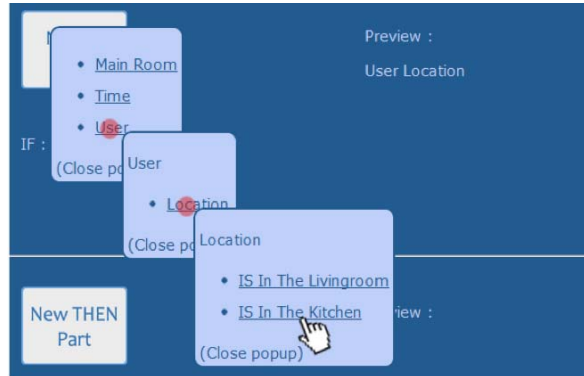
**Figure 10**. Rule Creator interface.

influence the agent has over the rule creation and, by extension, how much influence/control the user has over the rule creation:

- *Full autonomy*: the agent monitors the environment, learns the user's behaviour, automatically creates rules accordingly, and is able to make rules active in the system by increasing its confidence level,  as described in Section 3.
- *High autonomy*: the agent monitors the environment, learns the user's behaviour and generates rules accordingly but the rules can only become active in the system when they have been confirmed by the user. The user is presented with the opportunity to accept, reject or edit rules at the confirmation stage.
- *Low autonomy*: the user programs the rules using a GUI. The user is assisted by the agent presenting suggestions for rules upon request.
- *No autonomy*: the user programs the rules using a GUI.

At the bottom level of autonomy (*no autonomy*) the agent has no influence and the user maintains maximum control of how, when and what rules are created and used in the system, however, the trade-off is that a much greater cognitive load is placed on the user (decreasing user convenience). If the user selects the *no autonomy* level for a given type of device (lights, air conditioning, TV, and curtains), then all actions the user performs with this type of device are hidden from the agent and hence the agent is unable to learn behaviour rules for these devices.

If the user selects the *low autonomy* level for a given type of device, then the agent is able to see and learn from the user's actions with these types of devices but is greatly restricted in how much confidence it can assign to any behaviour rule that it learns. The effect of this is that agent-learnt rules cannot become active in the system but remain as potential rules only, as described in Section 3. These potential rules then form the basis for suggestions that the agent gives the user upon request to aid the user in creating rules. The suggestions are chosen based on the confidence levels of the potential rules, with the rules with higher confidence being chosen to form suggestions first. If *low autonomy* level is selected for a device that doesn't yet have any potential rules learnt for it, then the suggestions are based on a number of default pre-programmed behaviour rules.

At the *high autonomy* level, the agent is allowed to see and learn from actions and the amount of confidence that the agent may assign to learnt behaviour rules is increased from the *low autonomy* level. With a *high autonomy* setting, once the agent assigns its maximum allowed confidence to a rule (set at the just below level at which a behaviour rule become active, as described in Section 3) the user is notified and has the option to either accept, reject or edit the rule. If the user accepts the rule, then the confidence level is increased and the behaviour rule becomes active. If, however, the user rejects the rule, then is confidence is greatly reduced and it remains as a potential rule. The user also has the option to edit the rule before accepting it if they decide that the agent-learnt rule requires some tweaking. Note that this action effectively reduces the autonomy level slightly from the *high autonomy* setting as the influence that the user is having over the rule is increased and the influence of the agent is slightly decreased.

At the *full autonomy* level, the agent is unrestricted and can freely monitor the user's actions, learn behaviour rules and also assign full confidence so that the agent-learnt rules can become active in the system without knowledge or consent from the user. Naturally, the user is free to edit or delete any active agent-learnt rule (as well as any rule they created themselves) in the system using the rule viewer. Thus, an agent can never have absolute autonomy in the system and the user can always ultimately have the last say and maintain control; however, such a low level of control may cause a high level of discomfort and annoyance if the agent is prone to making errors.

After being instructed on how to use the system and having a chance to try out the four different autonomy levels, the participants conducted three trials in which they were asked to create (or have an agent create) a number of automated behaviours rules in the system, which took the form of an '*IF state THEN action*' mapping, for example, *IF the user is in the Living Room, THEN turn on the television*. As well as containing environmental state, the *state* antecedent could also contain a time variable. Since the trials were scenario based and over a very short period of time, the system time variable was simulated to be measured in days, with each day being split into four time stages. The time allowed for each trial was unlimited but most participants took between 10 to 15 minutes to complete each trial. During the trials the participants were free to choose which ever level of autonomy they wished for each type of controllable device and were able to change their mind at any time. After the participants had completed all three trials, they were interviewed to assess their opinions of the different autonomy levels, which levels of autonomy they preferred for which devices, and their opinions of the adjustable autonomy mechanism.

The first trial involved creating quite simple rules inspired by a basic (and very abstract) daily routine of when certain devices might be used. The task was to create the following automated behaviours based on the time of day and user location only:

- In Time Stage 1 the Curtains should open.
- In Time Stage 4 the Curtains should close.
- In Time Stage 3 the Dimmer Lights should be set to level 7
- In Time Stage 3 the Air Conditioning should be turned on.
- When the user enters the Living Room the TV should be turned on.

The second trial was again based on the scenario of how devices may be used on a day-to-day basis but in this trial the users were asked to create a set of more complex automated behaviours:

- If the temperature in the iSpace is warm or hot then the Air Conditioning should be turned on in Time Stages 1 and 3.
- The Air Conditioning should always be turned off during Time Stages 2 and 4.
- If the light level is bright or very bright then the curtains should close and the lights should be set to level 6. However, the lights should always be turned off in Time Stage 3.

The third trial was based on the scenario of how someone might want to automate certain devices based on their daily television viewing habits. The user was asked to create the following behaviours to control the television, curtains and dimmer lights:

- In Time Stage 1 the TV should be turned on.
- When the user is in the Living Room and the Light Level is Bright the Curtains should be closed and Dimmer Lights should be set to level 4.
- When the user is in the Kitchen the curtains should be open and the Dimmer Lights should be off.
- In Time Stage 2 the TV should set to channel 2.
- In Time Stage 3 the TV should set to channel 5.

After the participant had completed all three of the trials, the investigator interviewed the participant to assess their opinions of the different autonomy levels and the adjustable autonomy system. The interview took a semi-structured approach [38], which allowed the discussion to be open ended and adaptable to the participant's experience during the trials yet still aimed to discuss the same set of major points with each participant. The major points discussed align with the questions asked in the online survey, described in Section 4. The major points discussed with the participant are outline below:

- What was the participant's experience of the trials and which autonomy levels did they use?
- What are their preferences between the different autonomy levels and why?
- Would they change their choices/preferences if they were actually living in the iSpace?
- Do any of the autonomy levels raise any specific concerns with the participant and would they avoid a certain level for a certain reason?
- Does the participant think it is useful to change the autonomy level at different times if they were living in the iSpace permanently?
- Do their preferred autonomy levels change between different devices, and if so what was it about the device that made them choose that level?
- If they were living in the iSpace, do they think it would be useful to set the autonomy level for individual devices?

Since the user trials were based on a scripted set of tasks, the actual usage data from the user trials (e.g. how the user created behaviour rules, which levels of autonomy they chose to use, their success rate, etc.) was not used in the analysis, as the results may have been too biased towards the specific tasks instead of being illustrative of how someone might live more naturally in a smart home. Thus, only the interview data was analysed, in which the participants discussed their opinions in a more general sense after experimenting with the adjustable autonomy system in the trials. It should also be noted that, due to the short length of the user trials, the agent learning mechanism had to be simplified to allow the agent to learn behaviour rules quickly.

This reduced the performance of the agent somewhat and hence may have had a negative effect on the participants' view of the agent. The following section discusses the results obtained from the user trials.

*5.1.   User Trial Results*

Twenty participants took part in the user trial experiments in total. Figure 11 shows one of the participants during a trial creating behaviour rules for the television and dimmer lights. The participants were 50% male and 50% female, from educated backgrounds and aged between 20 and 45 (one participant chose not to disclose their age). Only 20% of the participants said they use computers between 2 and 20 hours per week on average, 40% said they use computers between 20 and 40 hours per week on average and 40% said they use computers over 40 hours per week on average. The vast majority (80%) of participants said they have very little or no experience of computer programming and 75% said they have heard of a smart home or intelligent environment before.

Throughout the experiment, some heavily contrasting and interesting attitudes towards the different levels of autonomy were found. The participants were asked nominate one level as their most and least favourite overall. Figure 12 shows the percentage of participants who selected each level as their most favourite and Figure 13 shows the percentage who selected each level as their least favourite. It is clear that full autonomy was by far the least favourite; however, it did still have some people saying it was their most preferred level. Conversely, while the no autonomy level was selected as most favourite, it also had some participants stating it as their least favourite. Very few participants nominated either of the semi-autonomous levels (high and low autonomy) as their least favourite but 20% selected the low autonomy level and 25% selected the high-autonomy level as their overall favourite.

A number of the participants felt that the full autonomy level would be best suited to someone with a busy lifestyle. Many recognised that allowing the agent full autonomy could save a lot of time and effort as it saves them from having to program behaviour rules themselves initially as well as saving them from having to edit rules if their preferences/habits change over time, as the agent would autonomously pick up on



**Figure 11**. A participant using the Apple iPad to control and create behaviour rules for the television and dimmer lights.
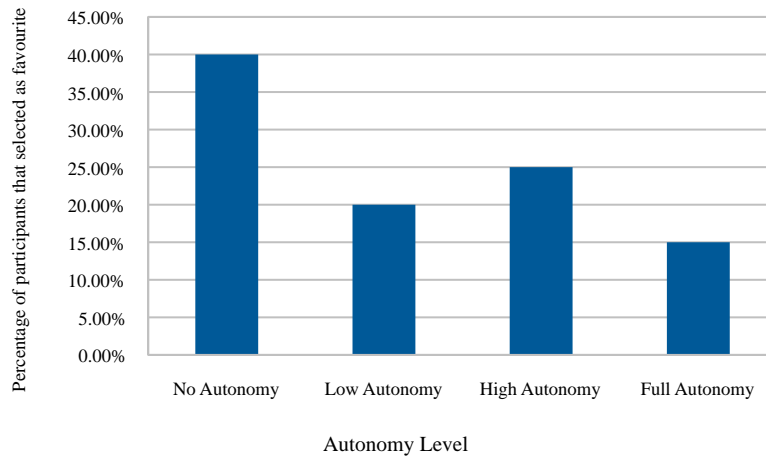
**Figure 12**. Graph showing the percentage of participants who selected each level of autonomy as their overall favourite
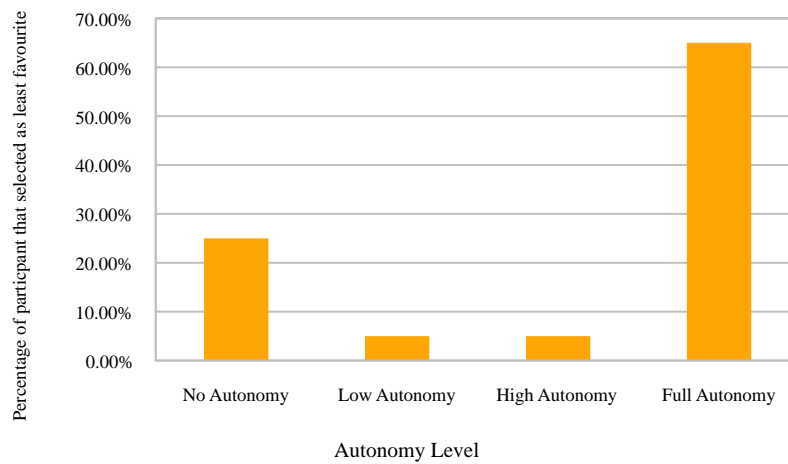


**Figure 13**. Graph showing the percentage of participants who selected each level of autonomy as their least favourite.

28

these. Some even said they would enjoy using it as it is 'very high-tech' and they'd like to see the artificial intelligence at work. One participant stated that they would like using the full autonomy setting if they lived alone because having everything arranged for you would make it feel like you are living with someone else and relieve their sense of loneliness. For most participants, the ability of the agent was a big factor that they thought might stop them choosing to use full autonomy. Some said they would probably use it to learn their more routine tasks and habits as they thought these would be easier for the agent to pick up on. Others said that they would first try out the agent and give it a chance to prove itself before they put their trust in it. A few said that they would avoid the full autonomy level altogether, as they felt that the agent would not be able to create effective rules and the thought of always having to correct rules the agent puts into the system seemed tedious. Privacy was another issue raised by some participants at the full level, although most said that having the ability to switch the agent to a lower level of autonomy eased these concerns a great deal.

As the high level of autonomy also depends heavily on agent learning, most of the same advantages and disadvantages were expressed by the participants. However, most preferred the high over the full level as it still allowed them to maintain a certain degree of control over what the agent learns. For example, one participant said they preferred the high autonomy level because they liked the fact that the agent would create behaviour rules for them but they preferred to have the agent "put it in writing first" – i.e. they preferred to be given the chance to see what the agent had learnt and subsequently accept, reject or edit the rule before it became active in the system rather than it all happening without their knowledge. Also, some participants thought that if they allow the agent high autonomy, it might pick up on their habits and behaviours, which they didn't realise they had. What's more, some thought it may be a good way to monitor their own and their family's habits. For example, one participant thought that allowing the agent to learn may be a good way to "keep an eye on how much TV the kids are watching". However, a selection of the participants said they might find the high level annoying as it is based on the agent providing suggestions as it desires. For example, one participant said they would avoid the high level as they didn't want to be "bothered by suggestions every time they did something". Another participant said that they would be wary of using the semi-autonomous (low autonomy and high autonomy) settings because from their past experience they have found systems that give suggestions can be very annoying. They gave the example of the search term correction functionality of online search engines, which when you conduct a search and the search system thinks you may have made a spelling mistake asks: "Did you mean:.....?". The participant said they find this annoying as they are already quite sure what they meant when they performed the search initially.

The majority of user trial participants were quite comfortable creating and editing rules using the rule creator. Hence, many didn't have any issues or concerns with both the low and no autonomy levels. There were some, however, that did find it a bit confusing and sometimes difficult to create rules themselves. What's more, there were some participants that felt that it would be very time consuming to create and constantly maintain a set of behaviour rules if they were living in a smart home. For example, one participant expressed that they wouldn't like to "spend time thinking of a list of suitable rules" for the system and would prefer an agent to do it for them. A number of participants stated also that they would not want to have to re-enter and edit rules if their preferences and habits changed over time. Conversely, there were also some who felt that it was actually better to change the behaviour rules themselves if

their behaviours changed as the agent may be slow to recognise the change and learn the new behaviours.

A small number of participants said that they would probably only use either the low or no autonomy levels. Some felt that doing so would allow them to "keep in touch with" the environment and objects around them and they wanted to make sure they didn't become dependent on the agent to do things for them. Some participants felt that using the low and no autonomy levels made the system much more flexible and allowed them more freedom to be creative with the rules. One interesting point raised by the participants was that they would prefer the no autonomy setting because they simply prefer doing things by themselves since they "were raised in an environment where they had to do everything for themselves". But the same participant speculated that their children, if born and raised living in a smart home, would perhaps more readily adopt artificial intelligence and autonomous-agents into their lives.

There were also a very small number of participants who decided that, if given the opportunity in real life, they may not use a smart home system at all, no matter the level of agent autonomy. Some reasons expressed for this were that they prefer a more "classic home" and wanted to "stay in contact with the physical environment", using things like a television remote and physical controls for devices. One participant felt very strongly about this, they said that having "a machine that takes control of our living space is taking our humanity" and they thought that human beings should strive to be as independent from machines as possible. Another participant expressed a big fear of technology being so deeply embedded in their life and hence wouldn't feel comfortable living in an intelligent environment even whilst using the lower levels of autonomy, as the system would still contain all the behaviour rules that they created to model their own behaviour. A similar concern over privacy of data was also expressed another participant. They revealed that they did not trust the government who could potentially use intelligent environments as a means of surveillance – as in George Orwell's book Nineteen Eighty-Four [2]. The participant also explained that using a lower level of autonomy might ease this concern slightly but not completely as the smart home system would still contain personal information.

The participants were asked to state which of the different levels of autonomy they would use for each of the device types if they were really living in a smart home. The answers are shown in Figures 14(a to d). For lights and curtains the answers were quite evenly distributed between all four levels. For the TV the participants preferred to maintain more control with the no autonomy level, and for the air conditioning the high-autonomy level was the clear favourite. As previously mentioned, many of the participants were unsure of the ability of the agent to learn and predict their behaviours adequately in a real life setting (rather than in a short experiment). Hence, they tended to choose the lower levels of autonomy for the devices for which they thought their usage patterns were less predictable or based more on personal mood and feeling – something the agent cannot sense in the experimental system. For many participants, the television was a prime example of this: the channel that people choose to watch and the times they choose to use the television depend heavily on the feeling of the person and can change a lot over a relatively short period of time.

Similarly to the television, many saw the usage of lights and curtains to depend heavily on personal feelings, and hence would prefer no or low autonomy; however, quite a few said they would rather use full or high autonomy as they felt their lights and curtain usage actually depends more simply on the time of day and/or brightness of the environment, and so decided it would be quite easy (and more convenient) for the agent
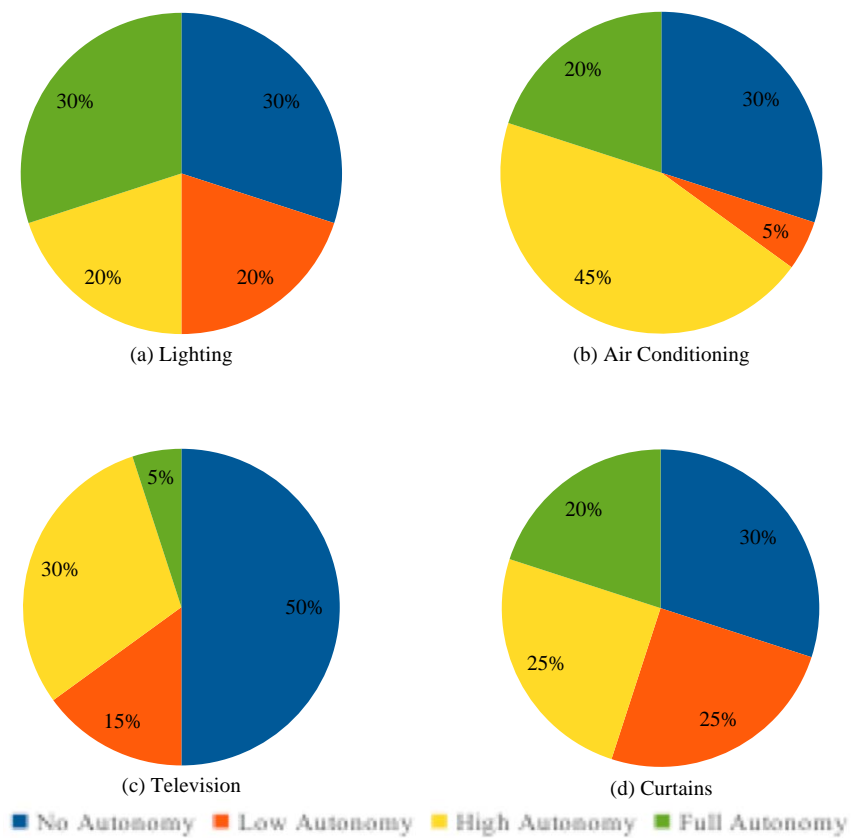
**Figure 14.** Pie charts showing percentage of participants that selected each autonomy level for the respective devices.

to deal with. Similar reasons were expressed by the participants for choosing the higher levels of autonomy for air conditioning; most felt that its usage is very routine and predictable as it is mainly dependent on the environmental state and time, and hence suitable for agent control. Moreover, some said that they wouldn't mind giving control of air conditioning and lights to an agent as the usage of these devices is generally not too delicate or sensitive, hence it doesn't matter too much if an agent makes mistakes. With the curtains, however, many did not want to give too much control to the agent as they would be worried that the curtains could open unexpectedly or at inappropriate times.

The vast majority of participants said if they were living in a smart home they would find the ability to change the level of autonomy useful and most said they think they would use different levels of autonomy for different devices. The exceptions to this were only one participant that said they would use full for everything and two that decided they would use the no autonomy setting for all of the devices if living in a smart home. Quite a few participants also mentioned that they could see themselves initially changing the levels of autonomy whilst still getting used to the system and eventually settling on certain levels at which they're most comfortable for each of the devices. Furthermore, some said they might start with a high level of autonomy to test the agent and give it a chance to "prove its ability and change the level of autonomy depending on its performance". A number of participants stated that it would be very important to be able to adjust the level of autonomy in "out of the ordinary situations". One example given numerous times was when you have friends visiting it would be important to turn down the autonomy, firstly, because the agent isn't going to take the needs of the new people into account in its decisions and, secondly, to stop the agent from learning new behaviours based on the actions and behaviour of the guests.

Some very interesting points have been raised and the opinions of the different levels of autonomy differ greatly between different people. Various different advantages and disadvantages for each of the different levels of autonomy were discussed by the participants. One major theme found throughout most of the experiments was that the participants were quite doubtful or wary of the ability of the agent and many felt that an agent would have to 'prove itself' before they would trust it to create or in some cases even suggest behaviour rules. What's more, the vast majority of the participants said that if they were living in a smart home they would use different levels of autonomy for different devices depending on what they perceive to affect their usages patterns; more specifically, whether they thought the device usage was affected more by environmental and temporal factors or if it was determined more by personal feelings and mood. Privacy was another big concern expressed by some of the participants. However, it seems that these concerns are not directly related to the use of autonomous agents and artificial intelligence but rather the pervasiveness and intrusiveness of the technology. The consensus between the participants seemed to be that, if they were living in a smart home, once they had found the autonomy settings that they are comfortable with, they would not change the autonomy settings much except perhaps for specific situations when wanted to stop the agent monitoring them, in which case being able to dial down the autonomy level would be very useful.

## 6. Comparative Results Discussion

After completing the online survey, it was clear that further research was needed, which included a practical element allowing participants to use an intelligent environment in real life, rather than form opinions based on their interpretation of a video. In part, this need was linked to our belief that users opinion can change based on their increasing knowledge of the system, or their increasing experience of it. Hence, the user trials in the iSpace were designed to give the participants a 'taste' of intelligent environments, and the participants were subsequently interviewed to see if their opinions differed to those given in the survey and also to gain more qualitative results to give better insight into the reasoning for their opinions.

In both the online survey and practical experiments, the usefulness for an adjustable autonomy mechanism in intelligent environments was made clear. In the online survey, the vast majority of the respondents stated that they would find the ability to set individual levels of autonomy for individual sub-systems very useful. For example, we saw that people would prefer to maintain a higher level of control (lower level of agent autonomy) for a more personal system such as entertainment and media services; whereas for other sub-systems, such as heating and lighting, people don't mind giving up a certain amount of control in exchange for increased convenience (a higher level of agent autonomy). This was mirrored in the user trials also: the majority of participants said that they would set the level of autonomy for each type of device depending on what affects their usage patterns for the given device the most, choosing a lower level of autonomy for the devices which depend more on the person and their emotions/feelings and a higher level of autonomy for devices which they use more based on the environmental state or time of day.

As shown by Figure 7, in the online survey the most popular levels of autonomy selected for the individual devices were the semi-autonomous (low and high autonomy) levels; however, as shown in Figure 14, in the user trials the preferred level was the no autonomy level, with the high autonomy level following closely behind. Unfortunately, it was not possible to implement all of the individual devices described in the online survey; however, for each of the different comparable devices the no autonomy level had a significantly higher popularity in the user trials than in the online survey. This increase in popularity may be due to the limitations of the user trials; for example, the short length of the experiments reducing the performance of the agent may have caused some participants to feel more negatively towards agents, as mentioned previously.

One common point that appeared in both sets of results was that people would change the level of autonomy depending on their experience with the system. One main reason cited for this was the user's confidence and familiarity with the system. Many felt that in the beginning they may like to have an agent help them to create rules but then reduce the agent's autonomy when they're more comfortable with the system. On the other hand, some people felt it would be better to start with a lower level of autonomy to allow themselves to explore the system more and then once they have a suitable set of rules configured, they would increase the autonomy level so the agent can maintain the rules. An interesting point that appeared more in the user trials was that people may initially doubt the agent's ability to learn from their actions effectively; hence, they would use a lower level of autonomy but, as most people also saw the benefit of having an agent to control devices in a helpful way, may increase the autonomy level if the agent could prove itself capable.

One of the most interesting results found in the online survey was that when the respondents were initially asked about which level of autonomy they preferred, they showed a strong preference towards the no autonomy level; however, later in the survey, when people were asked to think about managing the individual sub-systems in the intelligent environment, no autonomy was the least popular and high autonomy was the favourite. Although this shift in perspective wasn't seen as strongly in the user trial experiment, it was present for some of the participants. This is shown by the increase in popularity of high autonomy to almost the same as no autonomy when the participants were asked which levels of autonomy they would use for the individual devices. Moreover, a similar shift could be reflected by the majority of the experiment participants finding it necessary that an agent prove its ability before it would be trusted to operate with autonomy (something that it seems many of the user trial participants felt the agent did not manage to do during the experiment). In both cases, a higher level of autonomy would be selected when the user perceives that there is a larger amount of convenience to be gained. In the online survey, for example, a respondent's initial reaction may have been to maintain as much control as possible; however, when asked to think about actions such as turning on and off lights, something that most people do usually without even explicitly thinking about it, then they realised that there is a high amount of convenience to be gained from an autonomous-agent handling automation for the lights. Similarly, in the user trials, if the agent were to prove itself capable of controlling the lights well, then the user would be happy to allow it to continue as it provides high convenience; however, if the agent repeatedly makes mistakes then the convenience gain is much lower and perhaps replaced by a high amount of annoyance.

In both of these cases, the amount of convenience gained has to outweigh the negative effect of losing some amount of control, both of which are perceived differently by different people. For some people, the negative effect of giving up control is quite high as they have big concerns with privacy of personal information, issues with trusting an autonomous-agent or being annoyed with an agent's poor performance. All of these concerns were expressed by participants of both the survey and user trials, and are also in line with previous studies described in Section 1. Contrary to this, for others the perceived negative effect of losing some control may be quite small, if they are comfortable with the agent and whatever personal data is stored by the system. These tendencies were also shown by the user trial participants and online survey respondents. In fact, many of the user trial participants enjoyed experimenting with the agent during the trials and some were quite excited by the notion of having an agent control things in their home. Something that was made clear in the user trials was that the participants felt quite at ease with the agent working in their environment as long as they had the ability to turn it off. Something similar can also been seen in the autonomy levels people selected for individual devices in both experiments: many more selected the high autonomy level than the full. This suggests that people can indeed identify the benefit of have autonomous-agents working on their behalf but are much more comfortable if they can perceive that they ultimately have control, which in these experiments was achieved by offering a simple accept and reject option on the agent-learnt rules.

The findings of the online survey and user trials do broadly align with the previous studies of user needs and concerns described in Section 1. In summary the findings show that the overall factor which determines a user's preferred level of autonomy is the trade-off between control and convenience. However, the way in which a user

perceives each of these factors is highly individual and depends on a range of variables such as the user's experience with the system, the user's personal mood, the way in which the user wants to use specific devices, the performance of the agent, and even (as stated by one of the user trial participants) the way in which the user was raised from childhood. Given the shear diversity between these variables, equipping intelligent environments with an adjustable autonomy system is extremely useful as it allows the user to find their personal and very individual sweet-spot between control and convenience. This can be extended further by embedding an adjustable autonomy mechanism more deeply into the system architecture and allowing different levels of autonomy for different sub-systems, as in the AAIE architecture model.

Since these experiments were designed to give the participants a 'taste' of intelligent environments, they do not give a complete representation of how users would feel and react to different levels of autonomy if they were permanently living in an intelligent environment; however, the results do give strong indications of the reasons for and against the different levels of autonomy from a user's perspective. What's more, they show how people's opinions of agent autonomy can differ greatly not only from person to person but also change over time, in different locations and for different devices.

This work aims to raise awareness of the issues of extreme and static levels of autonomy amongst other researchers of intelligent environments and ambient intelligence systems. When designing and developing systems in these very user-centric areas, researchers are urged to experiment not only with different user interfaces but also with different levels of autonomy. Given the huge difference between the nature of ambient intelligent systems and more traditional desktop computing paradigms, researchers may find that users express unexpected concerns over either their own responsibilities in controlling the system or over allowing autonomous/intelligent agents to operate in the system. Researchers may even find that given the diverse nature of people, their final systems may have to employ an adjustable autonomy mechanism to be acceptable to wide user base.

## 7. Concluding Discussion

There is a long-standing debate over the use of autonomous-agents in ambient intelligence and intelligent environments. While many believe that research should focus on developing end-user driven systems, seeking to empower the user, many others maintain that intelligent environments should be autonomous-agent driven, minimising the work and effort required from the user. Both of these approaches have their distinct advantages, but they are not suitable for all as people's opinions and concerns regarding autonomy are highly individual, can differ greatly from person to person and change over time. This work explores how it is possible to make intelligent environments more dynamic and personalisable by equipping them with adjustable autonomy, which allows the user to alter the amount of influence autonomous-agents have over managing their intelligent environment. A recent online survey was conducted to gauge people's opinions on the use of autonomy in intelligent environments and a follow-up study of user trials was carried out, for which the Adjustable Autonomy Intelligent Environment (AAIE) model was implemented as an experimental system in the University of Essex iSpace.

The results strongly show that people would prefer different levels of autonomy in different situations and for different sub-systems of an intelligent environment. The results indicate that people's attitudes towards autonomy can be viewed, at a high level, as being determined by the trade-off between losing control and gaining convenience. However, it was found that how people perceive a loss of control or gain in convenience is highly individual and depends on a wide range of variables such as the user's experience with the system, the user's personal mood, the way in which the user wants to use specific devices, the performance of the agent, and even (as stated by one of the experiment participants) the way in which the user was raised from childhood, etc. Given the shear diversity between these variables, equipping intelligent environments with an adjustable autonomy system is extremely useful as it allows the user to find their personal and very individual sweet-spot between control and convenience.

This work aims to raise awareness of the issues of extreme and static levels of autonomy amongst researchers of intelligent environments and ambient intelligence. When designing and developing such user-centric systems, researchers are urged to not only consider their user interfaces but also the different levels of autonomy at which their systems can operate. Researchers may even find that, given the diversity of user's needs and concerns, their final systems may have to employ an adjustable autonomy mechanism to be acceptable to a wider user base.

Whilst these results may provide a valuable insight into people's attitudes towards autonomous agents, it is clear that there is need for further work in this area. This not only opens up opportunities and insight for computer scientists researching and developing ambient intelligence systems, but also provides opportunities for researchers of sociology and psychology to explore the underlying reasons for the user attitudes expressed in these findings. A more longitudinal study is currently ongoing at the University of Essex that allows the experiment participants to live with the adjustable autonomy system in the iSpace for a number of days.

## Acknowledgement

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