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Visualisation of a Three-Dimensional (3D) Object's Optimal Reality in a 3D Map on a Mobile Device

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Abstract: Prior research on the subject of visualisation of three-dimensional (3D) objects by coordinate systems has proved that all objects are translated so that the eye is at the origin (eye space). The multiplication of a point in eye space leads to perspective space, and dividing perspective space leads to screen space. This paper utilised these findings and investigated the key factor(s) in the visualisation of 3D objects within 3D maps on mobile devices. The motivation of the study comes from the fact that there is a disparity between 3D objects within a 3D map on a mobile device and those on other devices; this difference might undermine the capabilities of a 3D map view on a mobile device. This concern arises while interacting with a 3D map view on a mobile device. It is unclear whether an increasing number of users will be able to identify the real world as the 3D map view on a mobile device becomes more realistic. We used regression analysis intended to rigorously explain the participants' responses and the Decision Making Trial and Evaluation Laboratory method (DEMATEL) to select the key factor(s) that caused or were affected by 3D object views. The results of regression analyses revealed that eye space, perspective space and screen space were associated with 3D viewing of 3D objects in 3D maps on mobile devices and that eye space had the strongest impact. The results of DEMATEL *using its original and revised version steps* showed that the prolonged viewing of 3D objects in a 3D map on mobile devices was the most important factor for eye space and a long viewing distance was the most significant factor for perspective space, while large screen size was the most important factor for screen space. In conclusion, a 3D map view on a mobile device allows for the visualisation of a more realistic environment.

Keywords: 3D-Map; Eye-space, Perspective space, Screen-space

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1 Introduction

The introduction of Global Positioning System (GPS) technology for navigational assistance has had a profound effect on the ability to find physical locations with ease, transforming the social dynamics involved in traveling on the road [1]. However, people still become lost or are unable to follow directions to reach a specific destination. In certain unfortunate situations, a wrong turn can mean the difference between life and death [2].A three-dimensional (3D) map is a 2D or 3D visualisation of a 3D representation of a physical environment, which emphasises the 3D characteristics of the environment that are intended for navigational purposes [3]. Technically, the role of 3D maps is to provide more detailed information than is available from conventional 2D maps. Although 2D maps can represent any real or imagined space without regard to context or scale, they have the following limitations [4]: (1) The representation of landmarks entails symbols, legends and contour lines, which requires map-reading awareness; (2) The representation of route or road networks typically lacks orientation; (3) Such maps do not represent a realistic view (reality as it exists), requiring the translation of added legends that may require a certain level of expertise on the part of the user. The key benefit of a 3D representation is that it has a higher potential for accuracy in presenting spatial data. Additionally, it offers a better platform for multiple cues and small-scale features, which are better suited for locating and identifying unknown places. Creating a navigation tool on mobile devices with the help of a 3D model is undoubtedly a complex task but

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is certainly worth the investment [5]. It is tempting to also believe that moving from 2D to 3D visualisation will enhance user performance through natural support for spatial memory [6].

It has become possible to render large detailed 3D maps onto mobile devices at interactive rates. To date, however, only a few studies have investigated how 3D maps as part of mobile device applications can contribute to the knowledge of human spatial behaviour. The concept of a ”3D map view”, which is a tool that allows users to monitor their position (viewed from a ”satellite” position) on a small virtual screen embedded in the 3D world, was presented in [7]. This view has drawn attention to the level of detail required for 3D maps; however, until recently, when the graphics capabilities of mobile devices increased, 3D map visualisation on such small-screen tools was limited because very few mobile devices targeted graphical applications. Currently, though, mobile devices can render 3D at interactive rates [4]. Thus, to accelerate the rendering of a 3D map model on a mobile device, Jiang et al. [8] proposed to break down the model file into separate segments that would convert the 3D model into a data structure, such that the data would be organised and compressed, to enhance the rendering efficiency. One study has also suggested that users may prefer to combine augmented reality (AR) with 3D mapping as a navigational aid rather than using the AR view alone [9]. These findings clearly indicate that AR presents weaknesses with regard to navigation. Thus, a research question arises when considering how people will interact with digital 3D maps on a mobile device. ”*To what extent is a 3D map on a small-screen mobile device suitable for normal viewing?*” To answer this question, this study incorporated a quantitative survey with multi-criterion decision analysis on the factor(s) that influence the use of a 3D map view on a mobile device.

Subsequent to this section, the remainder of the paper is organised as follows. Section two discusses the conceptualisation of the work, and section three provides the research methodology and results. Section four presents a discussion. Section five provides the conclusions of this work.

2 Conceptualisation of a 3D map view on mobile devices

As stated by [10], visualisation amplifies cognition. Our visual systems are designed to perceive 3D surfaces and the shapes of the environment in which humans operate [11]. In addition to the common 3D transformations performed on vertices, such as translation, scaling, and rotation using coordinate systems, much information regarding 3D space coordinate conception, which includes eye space, perspective space and screen space, is perceived by the inward or outward turning or movement of one or both of the eyes at a different distance, resulting in vergence and accommodation. These phenomena give rise to depth perception of the real 3D space within eye space [12][13][14]. Blinn [15] showed that the eye can never have too much visualisation from screen space components $\tilde{x}_L$ and$\tilde{z}_L$ yield a straight line when one hyperbola is plotted against the other in the expression

$$\tilde{x}_L = \frac{A + B\alpha}{E + F\alpha}\,, \quad \tilde{z}_L = \frac{C + D\alpha}{E + F\alpha} \tag{1}$$

where A, B, C, D, E and F are 3D vector identities. Because eyes see shapes as parametric curves with two coordinates generated by hyperbolic functions of α for both $\tilde{x}_L$ and $\tilde{z}_L$, it is important to note that both $\tilde{x}_L$ and $\tilde{z}_L$ have the same denominator in equation 1, which causes the asymptotes of $\tilde{x}_L$ and $\tilde{z}_L$ to coincide because

$$\alpha = -{}^{E}\!/_{F} \tag{2}$$

When both asymptotes move to the origin when the parameterisation is altered by replacement, it becomes

$$\alpha' = E + F\alpha \tag{3}$$

This is then represented by the following straight line expression:

$$\tilde{x}_L = \frac{A + B\left(\frac{\alpha' - E}{F}\right)}{\alpha'} = \left(\frac{B}{F}\right) + \frac{1}{\alpha'}\left(\frac{AF - BE}{F}\right) \tag{4}$$

$$\tilde{z}_L = \frac{C + D\left(\frac{\alpha' - E}{F}\right)}{\alpha'} = \left(\frac{D}{F}\right) + \frac{1}{\alpha'}\left(\frac{CF - DE}{F}\right) \tag{5}$$

The proposition then results in the parametric equation of a straight line segment. Therefore, the representation conforms to equally spaced points in eye space that are equal in steps with α, and α', and these are transformed to non-equally spaced points in screen space [15]. Prolonged viewing of mobile devices and other stereo 3D devices leads to visual discomfort, aided by differing vergence and eye focal stimuli [16]. Humans are accustomed to the potential of momentarily seeing things with a single punctate eye to indicate a natural perspective [17]. Personal awareness, however, shows that the eye is not in the space, and imaginary spaces are subjective relative to the present in personal awareness [17]. For this reason, the subjective assessment of a 3D presentation within any medium is necessarily based on personal awareness.

The provision of 3D maps on mobile devices will improve users’ interactions with them and, thus, provide location information more accurately. However, this approach might not have an effect on the user’s visual perception. The users might not only need location-aware mobile guides in a 3D model, but may also occasionally need to have an idea of what an unfamiliar place looks like even before visiting it; the proposed services could be extremely useful on these occasions [18]. Because our human perception system perceives reality scenes from a 3D perspective, even when the scene is depicted on 2D media, 3D maps should be considered map-related representations and not maps in the classic sense. Mobile device screen sizes fall into three categories: large, medium, and small [19]. The corresponding sizes range from 4.5 to 6.5 inches, 3.0 to 4.4 inches, and less than 3.0 inches, respectively (see Figure 1).

Fig. 1: Visual display parts of the screen sizes of different mobile devices

With respect to recognition, 3D maps are recognised more readily from some viewpoints than from others; however, 3D map views are identified more easily than 2D map views, with a response time that decreases monotonically with increasing subjective quality. Nevertheless, how an individual perceives the true 3D presentation of reality on a mobile device might relate to the type of representation that is used. In the present study, three types of presentations were considered: pictorial realism vs. abstract views (Figure 2), 3D map projections vs. 2D map projections (Figure 3), and fixed viewpoints vs. manipulable viewpoints (Figure 4). At the heart of this classification lies the fact that 3D and 2D cartographic representations are inevitably selective and incomplete. Paper maps use symbolic conventions that tend to call attention to street names, landmarks, and crossings. However, there are no such conventions for 3D maps. For our study, we adopted a practical approach and collected some samples of 3D maps that fell within the above-mentioned categories, focusing on 3D systems that work on mobile devices based only on the fact that such 3D maps should follow an egocentric orientation towards reality [20]. In other words, information and the quality of its depiction on mobile devices must be adequate and able to display visual similarity to reality. For this reason, the following hypotheses were formulated:

Hypothesis 1 (H1): Eye space is associated with 3D viewing on mobile devices as a navigational aid.

Hypothesis 2 (H2): Screen space is associated with 3D map viewing on mobile devices for navigational aid.

Hypothesis 3 (H3): Perspective space is associated with 3D viewing on mobile devices as a navigational aid.

It has been proven that coordinates make it possible to address 3D space. This study will test the hypotheses formulated above to subjectively investigate the impact of 3D viewing of 3D maps on mobile devices and examine the most influential factors that facilitate the use of 3D maps on mobile devices to assist in navigation.

Fig. 2: 3D map view on mobile devices: pictorial realism vs. abstract views. (The sources of the three captions at the top from left to right are: Lynley [40], Tandon [41], and Baldwin [42] respectively).

Fig. 3: 3D map view on mobile devices: 3D map projection vs. 2D map projection

Fig. 4: 3D map view on mobile devices: fixed viewpoint vs. manipulable viewpoint. (The sources of captions at the top and the bottom are: Hurbanic [43] and Beeharee and Steed [44]

3 Methodology

Both a quantitative survey and DEMATEL analysis were conducted to understand the factor(s) that influence the use of a 3D map view on mobile devices for navigational assistance. The representational differences in 3D map views were considered. However, AR was not examined because a considerable body of literature has already investigated the interrelationships between AR on mobile devices and mobile maps [9]. Thus, the focus of this study was to investigate the factor(s) that influence the use of 3D maps on mobile devices for navigational aid. The quantitative survey evaluation was designed to generate statistically valid quantitative results. It is a hypothesis-testing evaluation that aims to generalise outcomes regarding people's navigational strategies to the general population while interacting with 3D representations on mobile devices. The utilisation of DEMATEL will help to identify the most influential factors from the results of the quantitative survey.

A quantitative survey relies mainly on a hypothesis deduced from a theory [21]. It uses standardised instruments to collect data on narrowly defined variables [22]. The reason for adopting a quantitative survey as part of this methodology was based on the nature of the research problem, which was confirmatory rather than exploratory; therefore, a deductive method was used primarily for description, explanation, and prediction of the research variables [23]. An additional justification for adopting a quantitative survey was that the outcome of the research entails theory testing by means of a conceptual model. This involves developing theoretically based hypotheses and collecting established data to test their viability [24].

DEMATEL extracts its dataset from the multiple choices ranking of factors observed by experts. Hence, the extracted factors must be mapped out to identify the relationship between them and determine the basis and significance of the evaluation criteria. The purpose of DEMATEL is to develop and highlight the interrelationships among evaluation criteria to determine cause and effect [25]. This technique established interactions among criteria based on the type and severity of ranked interactions, where the highest-ranked criteria had higher probabilities of being the cause criterion, whereas the criteria that were ranked lower were most significantly influenced by other criteria and, thus, were assumed to be the affected criteria [25][26][27]. This technique has been used in many areas to model the various influences of system components and develop decision-making competencies [28]. For this study, we used both *its original and revised steps* within the following procedure:

Step 1. The first step involves gathering experts' opinions on the bases of multiple choice questions intended to indicate the degree to which factor i affects factor j. Each expert's responses, X^n, are obtained, where $n = 1, 2, \ldots, n$. An $n \times n$ non-negative initial direct relation matrix is then constructed such that

$$X^n = \left[x_{ij}^n\right]_{n\times n} \tag{6}$$

where x_{ij} is the initial relation matrix; i and j are the cause and effect factors, respectively; and n is the number of responses for which $1 \le n \le q$. q is a matrix generated by $X^1, X^2, \ldots, X^q$, where ^{q} is the number of experts. This means that for each expert's responses, a matrix is constructed such that the diagonal elements of the matrix are set to zero because an element cannot influence itself. Therefore, an average matrix Z is generated by

$$Z = \frac{1}{q}\sum_{n=1}^{q} X^n. \tag{7}$$

Step 2: In this step, the matrix generated in the previous step is normalised using equation 8 to form a new matrix D, so that the sum of any row and the sum of any column in matrix D is within the range of [0,1]

$$D = Max\left[\max_{1\le i\le n}\sum_{j=1}^{n} x_{ij}, \max_{1\le i\le n}\sum_{j=1}^{n} x_{ij}\right] \tag{8}$$

Step 3: The total relation matrix T is constructed from matrix D generated in the previous step. The total relationship is then established if $\lim_{m\to\infty} D^m = [0]_{n\times n}$, where m is the indirect influence D^m. This means that the sums of each row and column of the matrix are between 0 and 1. Then, the total relation, which is the sum of $D+D^1+D^2,\ldots,D^\infty$, converges to zero matrix, where $T=D+D^1+D^2+D^3+\ldots+D^\infty$

$$T=\lim_{m\to\infty}\left(D+D^2+D^3\cdots+D^m\right)=D\left(I-D\right)^{-1} \qquad (9)$$

and where I is an $n\times n$ identity matrix. Unfortunately, $\lim_{m\to\infty} D^m \neq [0]_{n\times n}$ may not always converge to the null matrix $[0]_{n\times n}$ [28]. As a result, the total relation matrix will not converge to the null matrix, at which time DEMATEL becomes infeasible. At this time, a revised DEMATEL to matrix Z, which uses ε (where Z is any small added value to the maximum value of the sum of the row or column of matrix Z), is employed [28]. This measure ensures that for all cases, $\lim_{m\to\infty} D^m$ will converge to the null matrix $[0]_{n\times n}$. The sum of rows (r) and columns (c) of the total relation matrix was then calculated in equations 10 and 11.

$$\mathrm{r}=[r_i]_{n\times 1}=\left(\sum_{j=1}^{n} x_{ij}\right)_{\mathrm{n}\times 1} \qquad i=1,2,\ldots,n \qquad (10)$$

$$\mathrm{c}=[c_j]_{1\times n}=\left(\sum_{j=1}^{n} x_{ij}\right)_{1\times \mathrm{n}} \qquad j=1,2,\ldots,n \qquad (11)$$

where r_i and c_j represent the effects of criterion i on j, and if $j=i$, then the sum $(r+c)$ reveals the total effects given and received by criterion i, whereas the difference $(r-c)$ shows the net effect that criterion i contributed to the system. However, when it is positive, criterion i is a net cause, but when negative, criterion i is a net receiver. Finally, the threshold value (α) is calculated based on the experts' opinions. Thus, in this study, equation 12 is proposed in a manner similar to the study performed by [28]; hence, an interaction diagram was constructed based on the (α) value,

$$\alpha=\frac{1}{N}\sum_{i=1}^{n}\sum_{j=1}^{n} x_{ij} \qquad (12)$$

where N is the number of elements in the matrix computed by the average of the elements in matrix T to extract some minor effects were necessary. This means that effects below the threshold value were not selected for presentation of the impact relationships [27].

Step 4: The relationship diagram for the cause and effect was constructed in this step. Cause and effect are mapped out to indicate the interactions among the sub-construct, revealing the most important factors and how they influence others [26].

3.1 Population, Sampling, and Data Collection Techniques

The sample used for the quantitative survey and DEMATEL was drawn from metropolitan Kuala Lumpur and some parts of northern and southern Malaysia. Multiple methods exist for generating the correct sampling technique. Leedy and Ormrod [29], for instance, stated that identifying good samples for research depends on the research question itself. However, these chosen samples are also based on whether the research approach is quantitative, qualitative, or both. Analysis of pilot data contributed to the sampling criteria of this study. We chose simple random sampling because it is an appropriate technique in which meaningful in-depth data from the population are acquired [30]. Individuals are selected randomly, and their responses are collected and filtered based on experience to yield the most information about the topic under investigation. Convenience sampling was used for DEMATEL because this type of study recognises that some informants are more useful than others, and those individuals are more likely to provide insight and understanding [31]. In essence, the information required for this type of approach targeted experts who could provide a complete understanding of the research needs [30].

The sample size for the quantitative survey was based on the available individuals who had experience with navigation-aiding devices in general and/or navigation devices with 3D viewing on mobile devices specifically. Therefore, an estimated number of 350-450 subjects was anticipated for the quantitative survey, whereas 11 experts on 3D visualisation were selected for the DEMATEL analysis. The primary data collection technique for both a quantitative survey and a DEMATEL analysis within the stated population and sample frame entails the use of questionnaires. Indeed, there are advantages to using questionnaires as a means of data collection over the use of an interview, internet, mail, or telephone collection methods. Questionnaires, for example, are less expensive and easier to administer than personal interviews and allow confidentiality to be assured [29]. The questionnaire items were designed based on answers to the research questions, which were produced via some modifications to the previous closely related items from closely related research to be suitable for the present study. The outlines of the questionnaire included Likert -type answers with a range of seven responses for the quantitative survey and Likert -type answers with a range of five responses for the DEMATEL analysis. The participants in the quantitative survey were asked to rate the extent to which they agreed with given statements as follows: (1) strongly disagree, (2) disagree, (3) somewhat disagree, (4) neither agree nor disagree, (5) somewhat agree, (6) agree, and (7) strongly agree, whilst the experts for the DEMATEL analysis were asked to rate their agreement along a range from 0 to 4, representing "no influence", "little influence", "medium influence", "strong influence", and "very strong influence", respectively. The seven-level Likert scale in the quantitative survey was used because of its wider scope and range of participants' responses, which significantly affected the data analysis [31], while the five-level Likert scale measure is the standard score criteria for DEMATEL analysis.

The questionnaires for both the quantitative survey and the DEMATEL analysis were validated through a pre-test survey, which evaluated the questionnaires by testing them on a small sample of participants to identify and eliminate potential problems that might arise or to address an unforeseen fault that could potentially impact the results. This procedure allowed us to identify ambiguity in the wording of the items and to identify new items that needed to be included. Thus, the feedback obtained at this stage was included in the revised final questionnaire under the scale items as follows:

1. Eye space

By subjective analysis, "eye space" refers to the position within the visual field relative to the eye and the viewing area, and it pertains to eye direction and pupil diameter as well [32]. Respondents' views on the four scaled items within the eye space construct are considered to express the perceived adaptation to environmental demands for 3D objects on a 3D map. This effect is crucial, considering that eye space diminishes reality by way of appearance and 3D geometry [33]. Therefore, the responses regarding the extent to which respondents were comfortable with 3D objects that were occluded by other objects on the 3D map in the mobile device will assist knowledge discovery about what factors influence the eye space effects of visualisations of a 3D object on a 3D map, as will responses on whether the view was realistic to the viewer, was presented such that it enhanced visual cognition upon either prolonged viewing or at a glance, or led to visual discomfort. Considering this information, the following scaled items were used:

- I can see 3D objects that are occluded by other objects on a 3D map of my mobile device
- 3D objects of a 3D map on a mobile device are realistic to my eye
- 3D objects of a 3D map on a mobile device enhance my visual cognition
- Prolonged viewing of 3D objects or a 3D map on my mobile devices leads to visual discomfort

2. Perspective space

A 3D object within a 3D map on a mobile device used as a navigation aid indicates a realistic scene as people move through an environment. Users will change both their heading and their location relative to the surroundings [34]. During such changes, the 3D objects will update their changing orientations with respect to the physical scene. Perspective space, as a construct for this study, entails the appearance of the present scene to the eye, which then aims to create an illusion of reality [34][35][36]. Subjective evaluations, in contrast to objective assessments of the perspective space, are crucial in understanding and associating navigational aid with the 3D map on different mobile devices. To extract how people perceive 3D objects based on the relative distances of objects conveyed on their mobile devices, the following scaled items were used:

- I am satisfied with the size of 3D objects on a small-screen mobile device.
- I am satisfied with the size of 3D objects on a medium-screen mobile device.
- I am satisfied with the size of 3D objects on a large-screen mobile device.

3. Screen space

The screen space on mobile devices remains a drawback for mobile content delivery for use in a more realistic situation whilst walking outside [37]. This situation is closely tied to navigation because the mobile device is used as a navigational aid. An objective approach for maximising the efficiency of a small screen space has been proposed by [38]. However, there may be huge discrepancies between what people perceive in 3D maps on mobile devices and other presentational views. To determine the extent to which people can perceive 3D objects within the screen space on a mobile device, the following scaled items were used:

- 3D objects visible in a 3D map on a mobile device in an unobstructed range.
- The viewing distance from my eyes to 3D objects appearing on a mobile device's screen
- Zooming from small-scale and large-scale presentations of 3D objects on a mobile device

The scaled items are questionnaire items that were used for both the MCDA and the quantitative survey, with a few modifications. The modifications were necessary because for the MCDA, the aim was to extract the key item within a construct that exerted the highest positive influence on that construct. Unlike a regression analysis, in which the relationships of all of the items to the entire construct are examined, MCDA identifies a key item that impacts all of the other items within the entire construct . Thus, the scale items and their corresponding coding schemes used for MCDA were as follows:

1. Eye space

- How do you rate the influence of 3D objects that are occluded by other objects in a mobile device's 3D map on eye space? –**[Visual density: (E1)]**
- How do you rate the influence of eye space on the realism of 3D objects viewed in a 3D map on a mobile device? –**[Visual realism: (E2)]**
- How do you rate the influence of eye space on the visual cognition of 3D objects viewed in a 3D map on a mobile device? – **[Visual appearance: (E3)]**
- How do you rate the influence of the prolonged viewing of 3D objects in a 3D map on a mobile device on visual discomfort –**[Visual time: (E4)]**

2. Perspective space

- – How do you rate the influence of 3D objects in a 3D map on a mobile device when viewed from a short distance **–[Short viewing distance: (P1)]**
- – How do you rate the influence of 3D objects in a 3D map on a mobile device when viewed from a medium-range distance **–[Medium viewing distance: (P2)]**
- – How do you rate the influence of 3D objects in a 3D map on a mobile device when viewed from a long-range distance **–[Long viewing distance: (P3)]**

3. Screen space

- – How do you rate the influence of 3D objects in a 3D map on a small-screen mobile device –**[Small screen: (S1)]**
- –How do you rate the influence of 3D objects in a 3D map on a medium-screen mobile device –**[Medium screen: (S2)]**
- –How do you rate the influence of 3D objects in a 3D map on a large-screen mobile device –**[Large screen: (S3)]**

Each scale item under the main factor represents a sub-construct, which made it easier for the experts to rank each question by understanding the researcher's intended scope. This was better than providing many questions for a sub-construct to be used as the main construct.

Approximately 570 survey questionnaires were distributed for the quantitative survey to collect data through self-administered research assistance and web techniques. This number was double the expected number of responses because we anticipated a response rate of at least 50%, as noted in [30]. Finally, the data collected as part of the quantitative survey were analysed using both descriptive and inferential statistics implemented with SPSS. DEMATEL analysis was incorporated in the other part of the evaluation.

3.2 Response Rates and Respondent Characteristics

The estimated number of individuals intended for the quantitative survey ranged from 350 to 500, taken randomly in and around metropolitan Kuala Lumpur, as well as northern and southern Malaysia. This range was considered because the survey was focused on randomly obtaining experienced groups in related study areas. Ultimately, 570 questionnaires were distributed; of these, a total of 293 participants returned their completed questionnaires within five months. A substantial number of those who did not return their questionnaires did not provide any reason during the follow-up collections. Of the 293 returned questionnaires, usable responses were obtained from 167. This decrease was the result of double-ticking a single question, failing to answer more than 60% of the questions, or answering only a single option throughout the questionnaire. The 167 participants were all relatively low- to high-experienced individuals in their related areas according to their responses. Approximately 42% of the 167 were female. Approximately 75% of the participants considered 3D maps to be their favourite type of map for navigational assistance. In terms of age, approximately 69% of the participants ranged in age from 15 to 39 years, while the remaining 31% were 40 years old or above. Regarding educational background, only 9% of the participants had a high-school diploma, whereas approximately 47% had Bachelor's degrees and approximately 25% had Master's degrees, with the remaining 18% having PhD degrees. All participants worked in the related administrative (21%), educational (27%), business (24%), or technical (26%) field. However, their frequent primary mobility type, mobile device type, level of awareness of mobile applications, and level of awareness of 3D maps on mobile devices for navigation were sufficient to indicate that they were familiar with navigation and pedestrian navigation. Four of the eleven experts for the MCDA had Master's degrees, while the remainder were PhD degree holders. Three of the experts were female, and the rest were male. All participants in the MCDA were experts, with many publications in areas related to 3D visualisation for mobile devices.

3.3 Results of the Quantitative Survey

Both correlation and regression analyses were performed. The total number of survey items measuring the three variables of interest was 10. To measure relationships among the variables, the averages of the items for each variable were computed. Thus, these were the same items that were used during data screening to ensure the suitability of measuring those variables based on the treatment of missing data, assessment of outliers, assessment of normality, factor analysis, and reliability test.

Pearson's correlation coefficient (r) ranged from r = .504 to .872. The highest correlation coefficient was obtained from the relationship between eye space and screen space, in which there was a significant and strong positive relationship between the two variables. However, there was also a strong relationship between screen space and perspective space. A relatively moderate relationship was observed between eye space and perspective. To obtain an in-depth analysis, standard multiple regression analysis was conducted to evaluate how well a set of predictors predicted the use of the 3D map view on mobile devices for navigational assistance. The results are presented in Table 1.

The predictors were screen space, perspective space, and eye space, whereas the criterion variable was the 3D map view on mobile devices. The linear combination of screen space, perspective space, and eye space was significantly related to the 3D map view on mobile

Table 1: Multiple Regression Analysis

Model 1	**B**	**Beta**	**t**	**Sig**
(Constant)	1.724		5.186	.000
screen space	.551	.612	6.945	.000
perspective space	.566	.495	11.682	.000
eye space	.617	.653	2.436	.016
R^2	.594			
Adjusted R^2	.572			
F	124.964			
Sig	.000			

devices for navigational assistance, F(3,163) = 124.962, p=.000 at the 0.05 alpha level.

The multiple correlation coefficient for the sample was .771, indicating that approximately 59% of the variance in the 3D map views on mobile devices for could be explained by the set of predictors (screen space, perspective space, and eye space). Based on these coefficient results, the independent variables statistically and significantly contributed to the prediction of the 3D map view on mobile devices for navigation assistance. Eye space (beta = .65, p = .01 at the .05 alpha level) made the strongest contribution to the 3D view. The next was screen space (beta = .61, p = .00 at the .05 alpha level), followed by perspective (beta = .50, p = .00 at the .05 alpha level). The tolerance is the percentage of the variance in a given predictor that cannot be explained by the other predictors. Thus, the small tolerances indicated that 70-90% of the variance in a given predictor could be explained by the other predictors. When the tolerances were close to zero, there was high multicollinearity, and the standard error of the regression coefficients was inflated. A variance inflation factor greater than two is typically considered problematic; thus, the largest tolerance in this case is was .18 whereas the smallest VIF was 1.7. Thus, the results of the analysis support the following hypothesised relationships:

H1: Eye space is associated with 3D viewing on mobile devices as a navigational aid.

H2: Screen space is associated with 3D map viewing on mobile devices for navigational aid.

H3: Perspective space is associated with 3D viewing on mobile devices as a navigational aid

3.4 Analysis and Presentation of DEMATEL Results

Step 1: The 11 experts' responses were gathered based on the multiple choice questions described in section 3. Responses were used to construct $n \times n$ non-negative initial direct relation matrices using equation 6. The matrices generated included matrices E_1 to E_{11} for Eye space, P_1 to P_{11} for Perspective space, and S_1 to S_{11} for Screen space.

$$E_1 = \begin{bmatrix} 0 & 1 & 2 & 3 \\ 2 & 0 & 3 & 4 \\ 4 & 1 & 0 & 2 \\ 1 & 2 & 4 & 0 \end{bmatrix} E_2 = \begin{bmatrix} 0 & 2 & 4 & 3 \\ 2 & 0 & 2 & 3 \\ 1 & 1 & 0 & 2 \\ 4 & 3 & 3 & 0 \end{bmatrix} E_3 = \begin{bmatrix} 0 & 3 & 0 & 3 \\ 2 & 0 & 3 & 3 \\ 1 & 1 & 0 & 2 \\ 4 & 2 & 4 & 0 \end{bmatrix}$$

$$E_4 = \begin{bmatrix} 0 & 2 & 3 & 2 \\ 2 & 0 & 4 & 3 \\ 1 & 1 & 0 & 2 \\ 1 & 2 & 3 & 0 \end{bmatrix} E_5 = \begin{bmatrix} 0 & 2 & 3 & 3 \\ 2 & 0 & 4 & 2 \\ 1 & 1 & 0 & 4 \\ 0 & 3 & 4 & 0 \end{bmatrix} E_6 = \begin{bmatrix} 0 & 2 & 1 & 3 \\ 2 & 0 & 3 & 3 \\ 4 & 3 & 0 & 4 \\ 1 & 2 & 3 & 0 \end{bmatrix}$$

$$E_7 = \begin{bmatrix} 0 & 2 & 3 & 1 \\ 4 & 0 & 4 & 3 \\ 1 & 1 & 0 & 2 \\ 1 & 3 & 4 & 0 \end{bmatrix} E_8 = \begin{bmatrix} 0 & 3 & 4 & 3 \\ 2 & 0 & 3 & 3 \\ 1 & 1 & 0 & 4 \\ 0 & 3 & 1 & 0 \end{bmatrix} E_9 = \begin{bmatrix} 0 & 1 & 4 & 4 \\ 2 & 0 & 3 & 3 \\ 1 & 1 & 0 & 2 \\ 4 & 2 & 3 & 0 \end{bmatrix}$$

$$E_{10} = \begin{bmatrix} 0 & 2 & 3 & 4 \\ 2 & 0 & 3 & 3 \\ 4 & 3 & 0 & 4 \\ 1 & 2 & 3 & 0 \end{bmatrix} E_{11} = \begin{bmatrix} 0 & 4 & 3 & 1 \\ 2 & 0 & 3 & 3 \\ 1 & 3 & 0 & 4 \\ 4 & 2 & 3 & 0 \end{bmatrix}$$

$$P_1 = \begin{bmatrix} 0 & 1 & 4 \\ 3 & 0 & 2 \\ 2 & 1 & 0 \end{bmatrix} P_2 = \begin{bmatrix} 0 & 3 & 2 \\ 2 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} P_3 = \begin{bmatrix} 0 & 3 & 4 \\ 2 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

$$P_4 = \begin{bmatrix} 0 & 1 & 4 \\ 3 & 0 & 2 \\ 0 & 1 & 0 \end{bmatrix} P_5 = \begin{bmatrix} 0 & 1 & 4 \\ 3 & 0 & 2 \\ 2 & 1 & 0 \end{bmatrix} P_6 = \begin{bmatrix} 0 & 4 & 2 \\ 2 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

$$P_7 = \begin{bmatrix} 0 & 3 & 4 \\ 4 & 0 & 2 \\ 2 & 1 & 0 \end{bmatrix} P_8 = \begin{bmatrix} 0 & 4 & 2 \\ 2 & 0 & 1 \\ 0 & 3 & 0 \end{bmatrix} P_9 = \begin{bmatrix} 0 & 3 & 4 \\ 2 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

$$P_{10} = \begin{bmatrix} 0 & 3 & 4 \\ 3 & 0 & 2 \\ 1 & 1 & 0 \end{bmatrix} P_{11} = \begin{bmatrix} 0 & 3 & 4 \\ 3 & 0 & 2 \\ 1 & 1 & 0 \end{bmatrix}$$

$$S_1 = \begin{bmatrix} 0 & 2 & 3 \\ 2 & 0 & 1 \\ 4 & 1 & 0 \end{bmatrix} S_2 = \begin{bmatrix} 0 & 4 & 3 \\ 3 & 0 & 2 \\ 2 & 1 & 0 \end{bmatrix} S_3 \begin{bmatrix} 0 & 2 & 4 \\ 3 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}$$

$$S_4 = \begin{bmatrix} 0 & 2 & 3 \\ 2 & 0 & 1 \\ 0 & 4 & 0 \end{bmatrix} S_5 = \begin{bmatrix} 0 & 3 & 4 \\ 3 & 0 & 2 \\ 0 & 1 & 0 \end{bmatrix} S_6 \begin{bmatrix} 0 & 3 & 3 \\ 3 & 0 & 2 \\ 2 & 1 & 0 \end{bmatrix}$$

$$S_7 = \begin{bmatrix} 0 & 3 & 3 \\ 3 & 0 & 2 \\ 2 & 1 & 0 \end{bmatrix} S_8 = \begin{bmatrix} 0 & 3 & 4 \\ 2 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} S_9 = \begin{bmatrix} 0 & 0 & 4 \\ 2 & 0 & 1 \\ 2 & 1 & 0 \end{bmatrix}$$

$$S_{10} = \begin{bmatrix} 0 & 3 & 4 \\ 3 & 0 & 2 \\ 1 & 1 & 0 \end{bmatrix} S_{11} = \begin{bmatrix} 0 & 3 & 4 \\ 2 & 0 & 2 \\ 2 & 1 & 0 \end{bmatrix}$$

The average matrixes, Z_e for Eye space, Z_p for Perspective space, and $Z_s$for Screen space, were calculated using equation 7. These represent the initial direct relation matrices, which are the averages of the 11 experts' responses on Eye space, Perspective space and Screen space, respectively.

$$Z_e = \begin{bmatrix} 0 & 2.1818 & 2.7273 & 2.7273 \\ 2.1818 & 0 & 3.1818 & 3 \\ 1.8182 & 1.5455 & 0 & 2.9091 \\ 1.9091 & 2.3636 & 3.1818 & 0 \end{bmatrix}$$

$$Z_p = \begin{bmatrix} 0 & 2.6364 & 3.4545 \\ 2.6364 & 0 & 1.5455 \\ 0.7273 & 1.1828 & 0 \end{bmatrix}$$

$$Z_s = \begin{bmatrix} 0 & 2.5455 & 3.5455 \\ 2.5455 & 0 & 1.5455 \\ 1.4545 & 1.1818 & 0 \end{bmatrix}$$

Step 2: In this step, the normalised initial direct-relation matrices D_e, D_p, and D_s for Eye space, Perspective space and Screen space, respectively were calculated using equation 8. We applied a revised DEMATEL to matrices Z_e, Z_p and Z_s to calculate matrices D_e, D_p, and D_s, respectively, where we introduced ε as 0.00001 in each case and added it to the sum of the third column for matrix Z_e (9.09090), which had the highest value, resulting in 9.09091 [41], while the sum of first row in matrix Z_p had the highest value, 6.0909. When added to ε to obtain 6.09091, the highest value obtained for Z_s was in the first row, 6.091. The ε was then added, yielding 6.09101. Hence, we normalised matrices Z_e, Z_p and Z_s by using equation 8 and obtained the normalised initial direct-relation matrices D_e, D_p, and D_s;

$$D_e = \begin{bmatrix} 0 & 0.24 & 0.3 & 0.3 \\ 0.24 & 0 & 0.35 & 0.33 \\ 0.2 & 0.17 & 0 & 0.32 \\ 0.21 & 0.26 & 0.35 & 0 \end{bmatrix}$$

$$D_p = \begin{bmatrix} 0 & 0.4328 & 0.5672 \\ 0.4328 & 0 & 0.2537 \\ 0.1194 & 0.194 & 0 \end{bmatrix}$$

$$D_s = \begin{bmatrix} 0 & 0.4179 & 0.5821 \\ 0.4179 & 0 & 0.2537 \\ 0.2388 & 0.194 & 0 \end{bmatrix}$$

Step 3: In this step, we calculated the total relation matrices$T_e, T_p$and T_s using equation 9. These matrices model the total cause-and-effect relationships among the sub-constructs.

$$T_e = \begin{bmatrix} 0.7672 & 0.9803 & 1.3198 & 1.276 \\ 1.0162 & 0.8433 & 1.4298 & 1.1351 \\ 0.8215 & 0.8206 & 0.9309 & 1.1351 \\ 0.9228 & 0.9723 & 1.3247 & 1.0216 \end{bmatrix}$$

$$T_p = \begin{bmatrix} 0.4974 & 0.855 & 1.0662 \\ 0.7294 & 0.4683 & 0.7862 \\ 0.3203 & 0.387 & 0.2799 \end{bmatrix}$$

$$T_s = \begin{bmatrix} 0.684 & 0.9402 & 1.2187 \\ 0.8475 & 0.525 & 0.8802 \\ 0.5666 & 0.5204 & 0.4618 \end{bmatrix}$$

Experts suggested that we should use the threshold equation established in equation 12 because there is no standard consensus for calculating threshold, although many approaches are available. The standard is decided by expert opinions based on the nature of the interrelationships to avoid excessively complex relationships. Thus, the threshold values obtained for Eye space, Perspective space and Screen space using equation 12 were 1.0596, 0.5989 and 0.7383, respectively. Therefore, only those values above the threshold were considered when assessing the impact of the interrelationships (see Tables 2 through 4). Furthermore, the effects of one sub-construct are revealed from the values of $(r+c)$and $(r-c)$ represented in Tables 2, 3 and 4, respectively.

The total impact of the observed relationships based on the threshold values indicated that visual time **[E4]** was the only sub-construct among all of them that impacted itself; at an impact level of 1.0216, it was the most important sub-construct of eye space because it had the highest $(r+c)$value. Based on $(r-c)$, it affected the sub-construct of eye space because it had a negative value. Furthermore, it was observed that only **[E4]** impacted all of the eye space sub-constructs. The list of sub-constructs in order of importance based on $(r+c)$values for eye space was E4 >E3 > E2 > E1, while for Perspective space, the order of sub-constructs was P3>P1>P2, and the order for Screen space was S3>S1>S2. The entire impact of the interrelationships with cause and effect of each relation on Eye space, Perspective space, and Screen space sub-constructs are presented in Tables 2, 3 and 4, respectively.

Table 2: Eye space - total impact of interrelationships with cause and effect

	E1	E2	E3	E4	r	c	$r+c$	$r-c$	Impact
E1	0.7672	0.9803	**1.3198**	**1.276**	4.3433	3.5277	7.871	0.8156	Cause
E2	1.0162	0.8433	**1.4298**	**1.3707**	4.66	3.5277	8.1877	1.1323	Cause
E3	0.8215	0.8206	0.9309	**1.1351**	3.7081	7.0554	10.7635	-3.3473	Affected
E4	0.9228	0.9723	**1.3247**	**1.0216**	4.2414	14.1108	18.3522	-9.8694	Affected

Table 3: Perspective space - total impact of interrelationships with cause and effect

	P1	P2	P3	r	c	$r+c$	$r-c$	Impact
P1	0.4974	**0.855**	**1.0662**	2.4186	1.5471	3.9657	0.8715	Cause
P2	**0.7294**	0.4683	**0.7862**	1.9839	1.7103	3.6942	0.2736	Cause
P3	0.3203	0.387	0.2799	0.9872	3.2574	4.2446	-2.2702	Affected

Table 4: Screen space - total impact of interrelationships with cause and effect

	S1	S2	S3	r	c	$r+c$	$r-c$	Impact
S1	0.684	**0.9402**	**1.2187**	2.8429	2.0981	4.941	0.7448	Cause
S2	**0.8475**	0.525	**0.8802**	2.2527	2.0981	4.3508	0.1546	Cause
S3	0.5666	0.5204	0.4618	1.5488	4.1962	5.745	-2.6474	Affected

Step 4. The relationship diagrams are drawn to indicate cause and effect diagrammatically by mapping out the interactions among them. Figures 5, 6, and 7 show the impact relationship maps for the Eye space, Perspective space, and Screen space sub-constructs, respectively. In Figure 5, E3 and E4 were affected by E1 and E2, while P3 was affected by P1 and P2 in Figure 6, and S3 was affected by S1 and S2 in Figure 7.

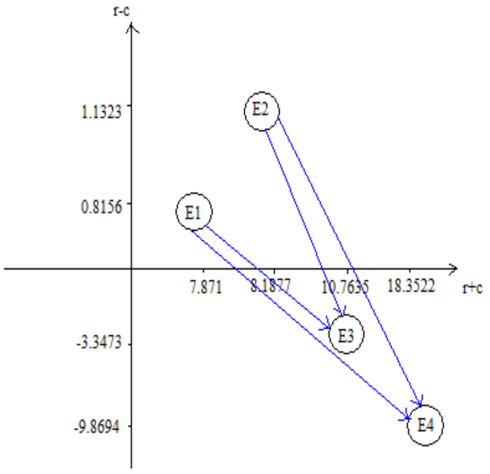

Fig. 5: Eye space relationships diagrams

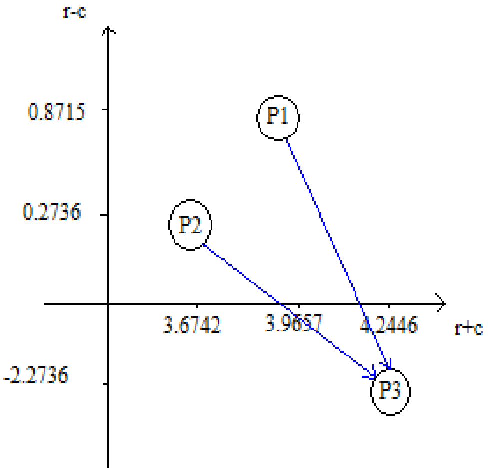

Fig. 6: Perspective space relationships diagrams

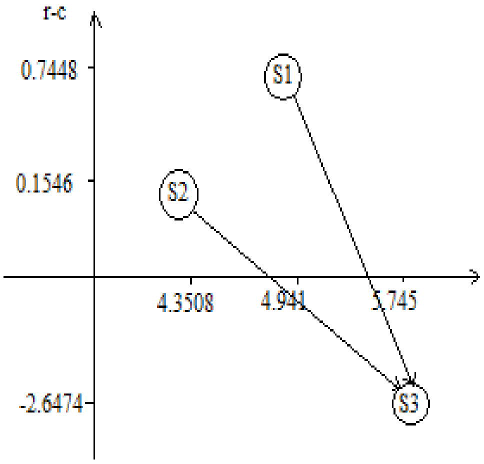

Fig. 7: Screen space relationships diagrams

4 Discussion

This study utilised two approaches to evaluate the key criteria for visualising 3D objects seen in 3D maps on mobile devices used for navigational aid. The first approach entailed a quantitative survey intended to rigorously explain participants' responses. The analysis of those responses identified three important issues in the use of 3D map views on mobile devices. The subjects pertained to eye space, perspective space, and screen space with regard to the use of the 3D map view on mobile devices. Although other issues were raised, the entire analysis demonstrates that the use of 3D maps on mobile devices for navigational assistance is a new and up-and-coming feature technology. However, individuals remain sceptical about the opportunities that such devices will provide for aiding navigation. Statistical analysis on the quantitative study intended to test three hypotheses showing that eye space, perspective space and screen space are each associated with 3D viewing on mobile devices, of which eye space had the strongest contribution. Few studies have been conducted with regard to how 3D maps function as part of mobile device applications that contribute to the knowledge of human spatial behaviour in terms of the engagement and disengagement of 3D map interactions used for navigation [20], [4]. Some studies have focused on field experimental investigations of the usage and usability impact of 3D maps on mobile devices for navigation assistance [9], while others have focused on service-aware mobile apps [39]. The results of such studies are bound to significantly diverge from reality because 3D maps on mobile device systems represent a complex problem, and design solutions can be contradictory; in particular, as the visualisation of the 3D details on a mobile device becomes more realistic, the system becomes more demanding in terms of mobile device computing resources [4]. Navigation task efficiency while interacting with 3D representations on a mobile device is then a highly context-sensitive issue. It is unclear whether more users will be able to identify the real world as the 3D map view on a mobile device becomes more realistic. What this study does accomplish, compared to the findings of previous studies, is to advance and validate the underlying key attribute(s) of viewing 3D objects on a 3D map on a mobile device through an examination of the links between what is obtained in the field and what people actually know about 3D maps on mobile devices. DEMATEL, a multi-decision criteria technique, was used to study the interrelationships between factors evaluated in the quantitative survey to make a decision about which key factor affected the 3D object views on the 3D map on mobile devices. We re-evaluated those factors and resolved them into the following: (1) Eye space: visual density (E1), visual realism (E2), visual appearance (E3), visual time (E4). (2) Perspective space: short-range viewing distance (P1), medium-range viewing distance (P2) and long-range viewing distance (P3). Likewise, we transformed Screen space into small screen (S1), medium screen (S2), and large screen (S3) categories. The result shows that the visualisation time (E4) that is attributed to the prolonged viewing of 3D objects in the 3D maps on mobile devices is the most important factor of the Eye space sub-construct, whereas the long viewing distance (P3) of 3D objects on a 3D map on mobile device are the most important sub constructs of perspective space. The large-screen (S3) sub-construct of screen space was the most important, which pertains to the visual appearance of 3D objects in 3D maps on large screen size mobile devices. The results of DEMATEL analysis also showed that visualisation time (E4), long viewing distance (P3), and large screen (S3) are the most affected sub-constructs among all of those considered.

In general, the approach of this study was more comprehensive, analysing the visualisation of a 3D object's optimal reality in a 3D map on a mobile device. The 3D implementation was in the context of utilising a mobile navigational system. Different users' understandings could yield new knowledge about the factors influencing the use of 3D maps on mobile devices. The results of this study can help to define guidelines for associating mobile devices with navigation applications to ensure that the content reaches the appropriate and targeted users. For that reason, we utilised the theory stating that visualisation amplifies cognition [11] and incorporated a subjective research approach through descriptive and inferential statistics and MCDA with DEMATEL. The results produced by these two techniques confirmed our hypotheses and identified the key criteria that may have the most significant impact on the visualisation of 3D maps on mobile devices. Crucial to obtaining these results were the statistics and DEMATEL techniques used. The statistics included both correlation and regression analyses for hypothesis testing. These analyses were used to determine critical ratios, representing the indirect effects of screen space, perspective space, and eye space on 3D objects viewed on mobile devices. If one or more of these relationships was non-significant, researchers usually concluded that screen space, perspective space and eye space effects were not possible on the 3D views of the objects. Having obtained significant relationships by correlation analysis, as well as strong contributions from the entire constructs as indicated in section 3.2, suggests that our results yielded new and useful knowledge. Thus, statistical analyses yielded factors that influenced the use of 3D objects in 3D maps viewed on mobile devices for navigational aid. Furthermore, the DEMATEL results as explained in section 3.3 contributed to the extraction of the key criterion among “screen space”, “perspective space”and “eye space”that most impacted the visualisation of 3D objects. The combination of both statistical and DEMATEL analyses contribute to the guidelines for combining mobile devices with navigation applications to ensure that the applicable content reaches the appropriate and targeted users.

5 Conclusion

This paper presents an empirical investigation into the use of 3D maps on mobile devices to determine the factors that influence their usage via a quantitative survey and DEMATEL analysis. This approach was chosen to uncover users' perceptions of the 3D map view on mobile devices. We utilised the proven theory regarding the visualisation of 3D objects by coordinate systems. Eye space, perspective space, and screen space were used as the key variables for the empirical investigation. They were further subdivided to find the key factor(s) of visualising 3D objects in 3D maps on mobile devices. A quantitative survey and DEMATEL were used. The results of the quantitative study showed that eye space, perspective space and screen space were associated with 3D viewing on mobile devices and that eye space had the strongest impact. Whereas results from DEMATEL showed that the prolonged viewing of 3D objects on mobile devices was the most important factor related to eye space and the long viewing distance of 3D objects was the most important factor related to perspective space while large screen size was the most important for screen space. Finally, a 3D map view on a mobile device allows for the visualisation of a more realistic environment. These findings indicate that one's view of a 3D map on mobile devices is mainly influenced by perception. However, the 3D map will be perceived as a more useful navigational tool when it looks more realistic. Indeed, the 3D map view on a mobile device facilitates a more realistic visualisation of the environment.

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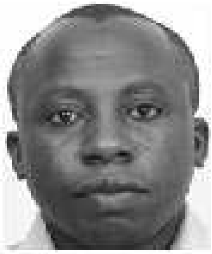

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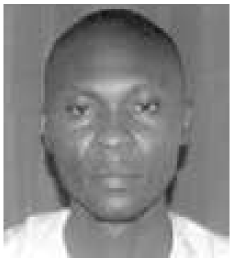

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