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The focus of neuropsychology is to understand the relationship between assessment results and everyday cognitive abilities and disabilities. However, the generalizability of traditional neuropsychological tests to real-life behaviors, the ecological validity, is compromised by the test environment, among other things. Neuropsychological tests are often completed in a laboratory setting that is typically quiet with few distractions. This is very unlike most everyday environments. The aim of the present study was to investigate the possibility of using a smartphone in standardized cognitive assessment. A short-term memory task was obtained from young adults in either an everyday-life environment or a controlled test setting at four time points during a day. Results show no significant differences between the task performances in both conditions. There was no indication that fatigue, tension, or environmental noise had an effect on task performance. High correlations between subsequent time points were found in the everyday-life environment, suggesting a high test–retest reliability and commitment of the participants. The present study demonstrates that smartphones can be used to assess cognitive functions outside a laboratory setting.

Key words: *behavioral analysis, behavioral neuropsychology, computer applications, ecological validity, short-term memory, smartphone, test environment*

INTRODUCTION

The function and dysfunction of cognitive abilities can be measured by neuropsychological assessments. Important aspects of the assessment are the standardized tests, which are the most effective tools for quantifying deficits (Evans, 2003). The focus of neuropsychologists is to understand the relationship between assessment results and everyday cognitive abilities and disabilities. However, the ecological validity, the generalizability of traditional neuropsychological tests to real-life behaviors, was found to be low (Chaytor, Schmitter-Edgecombe, & Burr, 2006; Silverberg, Hanks, & McKay, 2007) to moderate (Chaytor & Schmitter-Edgecombe, 2003; Gillen & Gernert-Dott, 2000) in most studies investigating ecological validity. The difficulty of investigating the ecological validity is that several factors influence the association between neuropsychological tests and daily life functioning, such as personal factors like emotion, mood, education level, motivation

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(Marcotte, Scott, Kamat, & Heaton, 2010), and stress (Luksys & Sandi, 2011).

Besides personal factors, one of the problems in demonstrating ecological validity in traditional neuropsychological tests is the test environment (Chaytor & Schmitter-Edgecombe, 2003; Marcotte et al., 2010). The intention of a neuropsychological assessment is to obtain the participants' best performance, often done in an artificial testing environment like a laboratory. This laboratory setting is typically quiet, with few distractions and with an examiner who is supportive. This is very unlike most everyday environments where the participant often has to perform tasks under distracting and unsupportive circumstances (Sbordone, 1996). Additionally, in laboratory conditions, the patient is a guest and the psychologist is the host. These roles may cause differences in the patient's behavior (von Koch, Wottrich, & Holmqvist, 1998).

To test participants in a more daily-activity environment, various studies have used smartphones or other handheld devices. Participants had to fill out a questionnaire or perform a certain task (Delespaul & deVries, 1987; Frings et al., 2008; Reid et al., 2009; Scholey, Benson, Neale, Owen, & Tiplady, 2012; Tiplady, Oshinowo, Thomson, & Drummond, 2009). The use of these tools has shown great benefits in exploring the psychological state and functions during daily activities. First, smartphones (or Web-based testing) can be used to access to large testing samples (e.g., Dufau et al., 2011). Secondly, bringing the test to the participant, instead of the participant to the test, saves time, costs of lab space, and equipment. Thirdly, tests can be administered more often, so that fluctuations in cognitive performance can be better detected (Kertzman, Reznik, Grinspan, Weizman, & Kotler, 2008). Finally, the cognitive performance can be measured in conjunction with other factors, such as sleep or mood states.

However, there are only a very limited number of studies that have used mobile devices to measure cognitive functions (Dufau et al., 2011; Scholey et al., 2012; Tiplady et al., 2009). Therefore, the aim of the present study was to investigate the use of a smartphone for cognitive assessment in young-adult participants. We used a letter span task (LST) that was developed for smartphone use and evaluated the short-term memory performance of the participants. The reliability of the test performance was evaluated by comparing the performance in a laboratory condition and an uncontrolled testing condition (i.e., during daily activities).

METHOD

Participants

In total, 36 Dutch young adults were included in the present study. Participants included friends, relatives, colleagues, and acquaintances of the researchers. All participated on a voluntary basis, without any compensation for the project.

Materials

Equipment. Testing was carried out on a Samsung Galaxy S Plus smartphone (Samsung Electronics Co., Seoul, South Korea). The dimensions of the phone are 122.4 mm $\times$ 64.2 mm $\times$ 9.9 mm. The display is a Super AMOLED capacitive touchscreen, 16 M colors, and the dimensions are 480 pixels $\times$ 800 pixels (diagonal 10.16 cm; $\sim$233 ppi pixel density). Further specifications can be found on various Web sites.

Questionnaire. At the start of each session, a short questionnaire was taken to identify the mood and environment characteristics of the participants. On a 9-point rating scale, ranging from "strongly disagree" to "strongly agree," participants had to indicate how gloomy, tense, and tired they were and how noisy their environment was at that moment. Also, participants were asked at which location they were at the time they conducted the test (home, university, school, outdoors, public place, or other). At the end of each session, participants were asked if they carried out the tests in peace and quiet ("Yes, I stayed at the same place to finish the test"; "Yes, but I had to seclude myself"; "No, I was distracted by my surroundings"; "No, I was distracted by another cause").

Letter span task. The LST was programmed in Adobe Flash and was intended to assess short-term memory. The task started with a short instruction on the smartphone. Participants were able to start the task by themselves by pressing the "start" button. A blue circle then appeared in the center of the screen. At the beginning, two "arms" with an oval shape at the end were attached to the circle and letters were successively presented for 500 ms within the circle. The letters that were presented in each oval were selected randomly for each test session. At the same time, one of the arms lit up (see Figure 1, left panel). After all the arms had lit up once in a clockwise manner, one of the arms lit up again and a question mark appeared in the center of the circle. Participants had to indicate on an ABC keyboard which letter corresponded with that specific arm (see Figure 1, right panel). After the response, again, letters were presented within the circle and arms lit up at the same time. When participants gave the correct response twice in a row, one arm was added. When the incorrect response was given twice in a row, one arm was removed. In total there were 30 trials. The automatically stored information included the difficulty, reaction time, and number of correct answers.

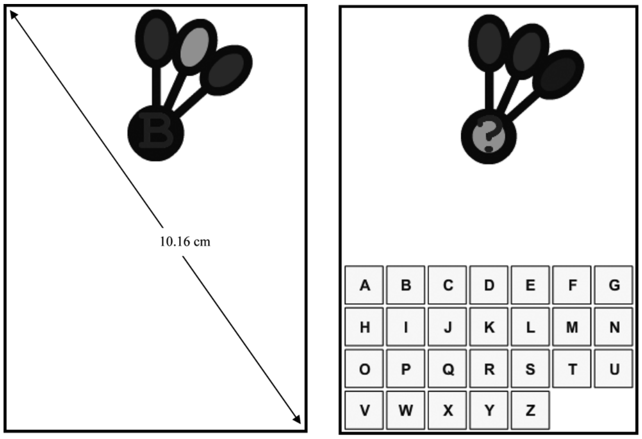

FIGURE 1 Schematic representation of the letter presentation in the letter span task. In the presentation phase, the ovals at the end of the arms lit up successively in a clockwise manner. The lighting up of each oval was associated with a letter that appeared in the middle circle (see left panel). After all arms were presented, a screen was prompted (see right panel) where the subject had to press the letter that corresponded with the letter that was presented in the respective arm. When two correct answers were given in succession, one extra arm was added in the next trial. When two incorrect answers were given in succession, one arm was removed.

Technical environment. As shown in Figure 2, the study started with signing up a participant (Login), including participant variables (e.g., age, sex, education). Also, the condition was indicated. The participant received an automatic e-mail message on the smartphone with a link to start the first session. Once the link was activated, the participant was asked several questions about the test environment. Subsequently, the LST was selected via the Web server (Runstudy) and was then launched and executed (TaskURL). At the end of the LST, information was sent and stored on the SQL server. These data could be monitored online and checked for completeness at any time during the study (see Figure 3). The data were stored with a timestamp that allows checking the starting and end time of the participants. This allowed filtering of tests that took too long (it is less likely that an LST was too short because participants can complete the task at a fast pace).

Via the Web server, information was refreshed and it was checked if the session was completed. After this was completed, the participants automatically received a new e-mail to start the next session (see next section).

Testing Protocol

Before the participants started the formal testing, they were first instructed in how to use the smartphone. This was done using a practice session in which the participants had to type in their personal data. In the same practice session, they had to perform the LST.

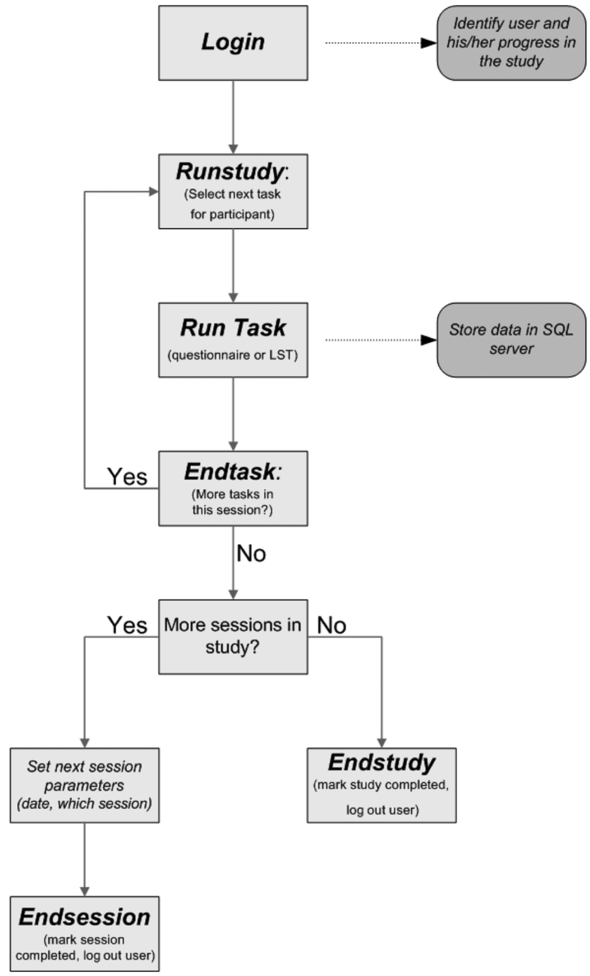

FIGURE 2 Stages of processing of the sessions and tasks.

After the participants indicated that they could use the smartphone, the first test session could be started. The test session could be done either the day before the testing or in the morning of the test day. The first test session (between 9 a.m. and 12 p.m.) was initiated by sending an e-mail message that contained a link to the Web site where the test was located. By clicking this link, the test session started. If the participants did not

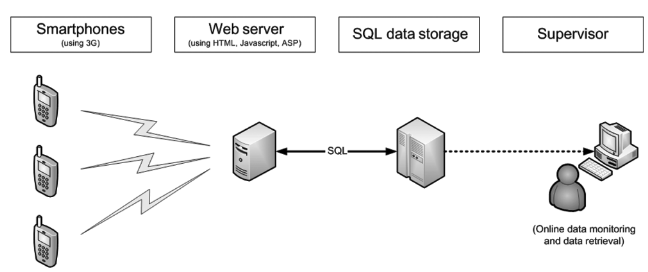

FIGURE 3 Schematic presentation of the connection, task performance via the Web server, and data processing via the SQL server. The data can be monitored online and retrieved in various formats from the SQL server.

start the session within 5 min, they received an additional e-mail message with the same link as a reminder. The participants were tested four times during 1 day. These sessions were also initiated by sending an e-mail message 3 hr after the previous session. So, in case a participant started the session immediately after receiving an e-mail message on each session, they would be tested at 9 a.m., 12 p.m., 3 p.m., and 6 p.m.. Each session took about 10 min to 15 min.

Data Analyses

Statistical analyses were performed using the Statistical Package for the Social Sciences Version 19. At first, data were screened for outliers and missing variables. Because there were some missing data (test sessions that were skipped, mostly due to technical/network issues), the missing values were calculated on the basis of performance on the previous and the next session (average value of these two sessions).

Differences in performance between the laboratory setting and the uncontrolled environment condition were analyzed using General Linear Model (GLM) repeated-measures analysis of variance, with the within-subjects factor being session (four levels) and the between-subjects factor being condition (laboratory/uncontrolled environment). The maximum number of remembered letters was used as an outcome measure, which indicated the difficulty level that a participant achieved.

To assess whether the LST performance could be attributed to environmental characteristics or to other personal variables, Spearman's correlation coefficients between these variables were evaluated. To evaluate the relationship between test results on different sessions, Pearson's correlations between the performances in the different sessions were computed.

All effects were tested at $p < .05$.

RESULTS

Participants

Twenty-six participants were included in the present study. Ten participants were excluded due to two or more missing data points (mostly due to technical issues). The 26 subjects (13 men, 13 women) ranged in age from 19 to 29 years, with a mean age of 23.12 years ($SD = 3.024$). Five participants had a medium education level, while all others had a high level of education. One half of the group was working and the other half were students. Thirteen subjects performed the tasks in a lab condition, while the other 13 performed the tasks in an uncontrolled environment.

Letter Span Task

There was no significant effect of condition, indicating that the amount of remembered letters was generally the same for participants in the controlled environment and those in the uncontrolled environment, $F(1, 24) = 0.28$, $p > .60$ (see Figure 4). In both conditions, there was a significant main effect of session, $F(3, 72) = 3.07$, $p < .05$, suggesting that there was a small but significant increase in the number of letters that were remembered. Evaluation of the orthogonal contrasts revealed a linear increase in performance, $F(1, 24) = 7.25$, $p = .01$. There was also a significant interaction effect between session and condition, $F(3, 72) = 4.10$, $p < .01$, which could mainly be explained by a quadratic relation, $F(1, 24) = 10.07$, $p < .01$. This was due to an inverse development of the number of letters that could be remembered in the two testing conditions. There were no differences between the two test conditions on the individual sessions (t values <1.65, *ns*).

Personal and Environmental Factors and Task Performance

Table 1 represents the Spearman correlations between the personal and environmental factors and the task performance within each session. In general, the correlation between feeling gloomy and task performance was relatively low on all test time points during the day, indicating that the task performance was not influenced by feeling gloomy at the time of testing. Concomitantly, the correlations between tension and task performance were very low on all time points during

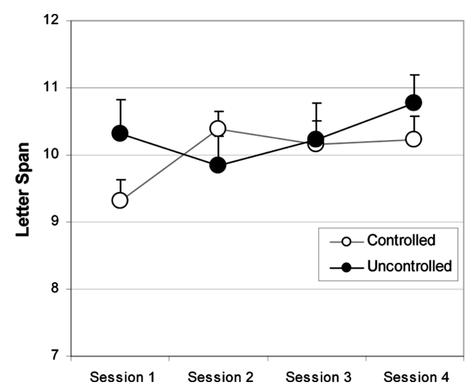

FIGURE 4 Mean amount of letters remembered in each session in the letter span task. There was no effect of test condition. There was a small but statistically reliable increase in the letter span task during the four sessions. A test condition × session effect was found, which could be explained by a different development of the performance in both sessions. No differences in the individual sessions were found. Values represent mean + standard error of the mean.

TABLE 1
Correlations (r_s) Between Ratings About Personal/Environmental Factors and Letter Span Task Performance in Each Session

	Letter Span Task Performance			
Factor	*Session 1*	*Session 2*	*Session 3*	*Session 4*
Gloomy	−.06	−.09	.29	.33
Fatigue	−.09	−.02	.18	.16
Tension	.09	.08	.49*	.16
Environmental Noise	−.22	−.14	.13	−.15

*Correlation is significant ($p < .05$).

the day, indicating that the task performance was not influenced by tension at the time of testing. As an exception, tension was correlated with the amount of remembered letters in the third session. Correlations between environmental noise and task performances were lower than .22 in each session, indicating that the task performance was not influenced by environmental noise at the time of testing.

Relationship Between Sessions

The intraclass correlation coefficient (ICC) was moderate in the laboratory condition, which indicates a moderate consistency in the performance of individual subjects on successive sessions. The ICC appeared to be higher in the uncontrolled environment condition than in the laboratory condition.

The correlations between the different sessions for the LST are shown in Table 2. Strong relationships between all subsequent sessions were found in the own environment condition. In the lab condition, significant relationships were also found between the first and second sessions and the third and fourth sessions, but not between the second and third sessions.

TABLE 2
Correlations (r) Between Performance on the Letter Span Task During Different Sessions During the Day, Per Condition

Condition									
Laboratory					*Uncontrolled Environment*				
	Session					*Session*			
Session	*1*	*2*	*3*	*4*	*Session*	*1*	*2*	*3*	*4*
1	—	—	—	—	1	—	—	—	—
2	.621*	—	—	—	2	.880**	—	—	—
3	.461	.422	—	—	3	.637*	.785**	—	—
4	.632*	.340	.660*	—	4	.734**	.881**	.754**	—
ICC = .522					ICC = .761				

ICC = intraclass correlation coefficient.
*$p < .05$. **$p < .01$.

DISCUSSION

The present study was conducted to examine if a smartphone could be used for neuropsychological testing. Therefore, we tested the cognitive performance (short-term memory using the LST) in a laboratory environment and in an uncontrolled environment. We found that participants readily learned to use the smartphone and that in most cases they were able to provide the requested input. Together, these findings indicate that smartphones can be used for neuropsychological testing in young healthy subjects.

Neuropsychological Testing

The present study provides strong evidence that cognitive performance can reliably be assessed using a smartphone, even in an uncontrolled environment. Two different explanations could be offered to support this conclusion. First, the performance of the participants was similar in the controlled and uncontrolled conditions. Thus, even without having a controlled environment, the performance is not different from a more standardized and controlled testing environment. This finding is not very surprising because it is known that young healthy subjects have the ability to focus attention on task-relevant information and ignore distractions (Guerreiro, Murphy, & van Gerven, 2010). This was confirmed by the finding that the correlations between the cognitive performance and the conditions of testing in both the controlled and uncontrolled environments were very low (except for one spurious correlation).

Secondly, it was found that the correlations between the successive test sessions were strong, especially in the uncontrolled condition. This indicates that the participants performed at a comparable level in the four successive sessions. Also, the variation of LST performance within participants was rather low. These findings suggest that the participants did not lose interest in performing the LST during one of the sessions. So, even without an experimenter being present, the subjects were dedicated and well motivated to perform the task. As mentioned, the correlations between LST performances were better in the uncontrolled condition than in the controlled condition. At first sight, this is surprising because it is generally assumed that the performance is more reliable when the participants are under direct supervision of an experimenter. Although this is one of few studies using smartphones applying this testing method, more studies are needed to replicate the current findings.

The data of the LST showed a small (about one letter for four sessions) but statistically reliable increase in performance. This indicates that the participants improved their short-term memory performance to some extent. In general, short-term memory is a stable function that cannot be improved. Three possible explanations could be offered for the improved LST performance. First, a general learning effect could explain this improvement during the four subsequent sessions. Of note, this learning effect could also be related to a more efficient strategy use. A second explanation for the improved performance could be related to the familiarization with the smartphone. Thus, it could be argued that the participants were not sufficiently trained during the first practice session to use the smartphone and they were getting more skilled with the use of the specific smartphone as testing progressed. We did not ask the participants which type of smartphone they used privately. It could be argued that participants with a Samsung phone would more easily work with the smartphone. On the other hand, the testing itself was done via the touch screen, which did not demand use of the specific technical operations that were required to operate the smartphone. Therefore, it is suggested that the effects of this factor may be limited. The third explanation for the improved performance could be related to using strategies that involve working memory. Thus, it has been shown that working memory performance can be enhanced with training (e.g., Gibson et al., 2012). Thus, it could be argued that subjects became more trained in applying a strategy that involved working memory.

In the evaluation of the relationships between subsequent sessions, it became clear that the overall relationship between subsequent sessions was moderate in the laboratory condition and high in the uncontrolled environment condition. These significant relationships give an indication about the high reliability of the tests, which in turn indicates that subjects were motivated and committed to perform the tasks each session. This is interesting because certainly in the uncontrolled environment condition, no experimenter was present to evaluate the motivation of the participant.

Technical Aspects

It should be noted that the tasks that were used on the smartphone were originally programmed for a personal computer (PC). Therefore, several technical issues needed to be considered when using smartphones for testing. The first issue was related to the caching of Web site information. When using a PC, the information is automatically refreshed when reloading the information. However, this feature is not the default setting of smartphones. In case this setting was not changed, the subjects were repeatedly asked to perform the same task in the same session. This problem was solved by forcing the smartphone to refresh information after a task.

A second issue was related to resizing of the task to make it workable on the smartphone. We used the Samsung Galaxy S Plus, which has a reasonable display size, to make the task clearly visible so participants could relatively easily type their answers (see Figure 1). The development of smartphones is a continuous process. At present, there are smartphones with larger displays, which would make it easier for subjects to perform the tests. Clearly, the size of the display needs to be determined on the basis of the tests one would like to use for the ambulant testing. In the present study, we used the same smartphone for all participants to control for the size and the appearance of the questionnaire and the LST. It would also be possible for participants to use their own smartphones. Even though this would limit the comparability between the presentations of the test, it would obviously reduce research costs and could easily increase the number of participants that could be included in the study.

A third technical issue that needs to be noted is the stability of the network. Clearly, there are differences in the stability of the network between different network providers. This may be different for other countries and needs to be addressed on an individual basis. Further, smartphones are, as a default setting, continuously searching for a better Internet connection (possibly also with other providers). Loss of network connections can lead to disruption of the task and loss of data (which occurred in our study on various occasions). This problem can be solved by selecting a specific provider. Also related to the networking function, the default setting of smartphones is that they can switch between Internet providers and thereby switch the Internet protocol (IP) address. Consequently, the identification of the smartphones by the server should not only be done on the identification of the IP address.

The data are directly saved on a server in a data matrix that can be retrieved in any output format depending on the specific needs of a study. Each data entry is given a timestamp, which allows for checking the duration of each test that was performed. It is relatively easy to extract the data from the SQL server from any connected PC. The data of the ongoing test can be accessed at any time.

Concluding Remarks

The present study is one of few studies using smartphones as a tool to perform a neuropsychological task (Dufau et al., 2011; Scholey et al., 2012; Tiplady et al., 2009). The present study shows that the ambulant testing of cognitive functions can be done using smartphones. The great advantage is that participants can be tested at a distance and that they do not need to come to the laboratory for each test. It was shown that the participants were motivated to perform the task even in the absence of an experimenter. Other advantages include easier access diverse participant populations and access to large samples (Dufau et al., 2011). Furthermore, tests can be administered more often, allowing for better detection of fluctuations in cognitive performance (Kertzman et al., 2008). Also, cognitive performance can be compared to other factors, such as sleep or mood, which creates the possibility of comparing effects of such personal factors between everyday-life assessment and a laboratory setting. Moreover, using a smartphone not only saves time, but it also saves costs of lab space, equipment, and administration. Clearly, further studies are needed to replicate the present data. Considering the numerous advantages and new opportunities this novel method could potentially have, further research using this method is warranted.

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