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DOI:
10.1145/3229434.3229451

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ABSTRACT
One potential method of improving the efficiency of human-computer interaction is to display information subliminally. Such information cannot be recalled consciously, but has some impact on the perceiver. However, it is not yet clear whether people can extract *meaning* from subliminal presentation of information in mobile contexts. We therefore explored subliminal semantic priming on smartphones. This builds on mixed evidence for subliminal priming across HCI in general, and mixed evidence for the effect of subliminal affective priming on smartphones. Our semi-controlled experiment (n=103) investigated subliminal processing of numerical information on smartphones. We found evidence that concealed transfer of information is possible to a very limited extent, but little evidence of a semantic effect. Overall, the impact is effectively negligible for practical applications. We discuss the implications of our results for real-world deployments and outline future research themes as HCI moves beyond mobile.

Author Keywords
Smartphone; subliminal priming; semantic priming; nonconscious behaviour change.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION
Interest in the effectiveness of subliminal, nonconscious techniques to influence user behaviour is growing in HCI [17,43,44,50,51,58]. This paper investigates the effectiveness of subliminal semantic priming on smartphones. Subliminal priming occurs where the showing of a stimulus (the *prime*) has some measurable effect on a person, despite them being unable to consciously recall it [15,44]. Subliminal *semantic* priming occurs where a person can extract *meaning* from primes, despite not being able to consciously recall them. A prime might provide information about an upcoming item that requires a response (a *target*) in order to speed up or improve accuracy in that response. For example, consider a number categorisation task where users have to respond whether a target number is more or less than 5. A prime that is also more or less than five, *congruent* with the target, may improve response times and accuracy. Congruent primes provide pertinent information about the target, so comparing their effects with incongruent primes can help to determine whether concealed transfer of information is possible.

To demonstrate whether meaningful *semantic* processing is occurring, rather than people simply forming associations between primes and targets that occur together (known as *stimulus-response processing* [31]), recent psychology research has used *novel* subliminal primes [38]. Novel primes are never displayed supraliminally as a target or part of a response choice. Since the novel primes are never consciously perceived, accurate responses to novel primes must indicate some semantic activation that associates the prime with the correct response [35,60]. Ocampo's experiment in a lab using desktop computers showed that novel primes can influence participant responses not only where there is a correct answer for a given task (a *forced-choice* trial) but also where there is no target and therefore no correct answer (a *free-choice* trial). The effects of this semantic processing were found to be similar to *repeat* primes, which appeared as both prime and target, which may be processed to a certain extent using the simpler stimulus-response mechanism [38].

In this paper, we explore whether similar novel vs repeat effects are found when using subliminal priming on a smartphone. Using smartphones provides a more realistic experimental setting than psychology labs, while still maintaining control over prime presentation such as how long primes are shown for [13]. Our work is intended as a first step to explore whether similar effects can apply in more realistic conditions.

If meaningful transfer of information is possible via subliminal channels, then the technique may have impact beyond simply influencing efficiency in interaction. It could also facilitate cognitive activation of concepts related to the prime. Because of this, subliminal semantic priming is starting to be explored in technology-mediated behaviour change applications via nonconscious goal priming [1,22]. Subliminal semantic priming of goals aims to make information about actions to achieve the goal more accessible by spreading activation through the prime's associative network. This accessibility may then make the goal-related actions more likely to occur [2,5,21,44].

Our work builds upon the technique of subliminal *affective* priming (improving the liking of stimuli through subliminal exposure) in our previous work [44]. This work instead focuses on the use of familiar stimuli, numbers. We contribute a novel investigation into subliminal *semantic* priming techniques on smartphones, showing that results seen in the lab are hard to replicate consistently in more realistic deployments. Overall, we find very small effects, which are inconsistent between novel and repeat primes across tasks. We therefore find little evidence that practical applications of the technique on smartphones will improve either interaction efficiency or concept activation.

RELATED WORK

Applications of subliminal priming in HCI

Despite the opportunities afforded by pervasive smartphone use [26], there have been few implementations of subliminal priming in less controlled contexts on smartphones and beyond mobile into wearables. HCI subliminal priming research often focuses on using the technique to improve the efficiency of interaction between people and computers by using the subliminal channel as a low-cognitive-cost way to transfer information to users [37]. Eliciting automatic responses via subliminal priming means that the responses are immediate, efficient and do not require limited cognitive resources to process [55]. The primary fields of HCI applications have focused on efficiency without distraction within the tasks of item selection; search; and reminding-without-distracting. More recent HCI research has explored the impact of cognitive activation beyond simple efficiency into affective priming; learning; and in nonconscious goal activation. As we outline below, the evidence is not equivocal across these research areas.

Item selection

Several researchers have focused on the use of priming to improve efficiency of item selection. Within a virtual reality context, Barral et al. found a significant impact of subliminal priming on correct target selection, but only for trials where reaction times were less than 1 second [7]. Caraban et al. developed a browser plug-in and researched the use of subliminal priming to guide selection by changing the opacity of key words [17]. They found evidence that subliminal priming delivered by altering opacity of word primes increased selection of a semantically related picture target compared to no-priming and supraliminal conditions.

Search

Another strand of subliminal research explores whether the technique can effectively direct attention in search tasks. Pfleging et al. explored subliminal priming on desktops as a means to improve visual search performance and found no evidence of an effect [41].

Avoiding distraction

An alternative use of subliminal priming is its use to *avoid* attracting attention, rather than to direct selection or search. De Vaul et al. explored the use of "memory glasses" to provide subliminal reminders of name/face combinations without distracting the user [24]. They suggest that the technique is particularly applicable to context-aware technology trying to determine the correct just-in-time point to interrupt a user, since incorrect subliminal notifications appear to be benign. This attention-avoidance strategy has also been applied in the driving domain to avoid distracting users during a potentially hazardous activity [52]. Both studies found little evidence for the effectiveness of subliminal notification strategies.

Affective priming

Subliminal priming can also be used to increase the liking of the prime. Subliminal *affective* priming associates a neutral stimulus with one that holds a particular affective value to influence the liking of the neutral stimulus [61]. Evidence shows that people prefer primes they have previously experienced to novel ones, which can extend to advertising brand preferences [11]. This preference for previously-experienced stimuli is known as the mere exposure effect [14]. We previously explored this effect in a semi-controlled experiment on smartphones, measuring the immediate effect of repeated showing of three different types of masked stimuli (polygons, words, photos) on subsequent liking of the stimuli compared to novel stimuli [44]. We found inconsistent effects across the stimulus types and suggest that the technique's effects are too unreliable to be used in mobile applications.

Learning

Chalfoun & Frasson used subliminal priming of correct answers in a 3D learning environment [18]. Their results showed that subliminally-primed learners showed improved accuracy and reduced response time when selecting one of three possible answers compared to non-primed learners. However, awareness checks were not reported, so it is difficult to determine whether the primes were subliminal.

Nonconscious goal activation

Subliminal goal priming assumes that goals can be activated outside of conscious awareness [6,22]. Some evidence of the effect has been shown in lab studies [1]. However, our implementation of subliminal goal priming on smartphones, where we tried to activate concepts relating to the goal of being "active", found no evidence of an effect [44]. Nonconscious goal activation has also been applied to special if-then planning goals known as implementation intentions [55]. Several HCI pilots have investigated using such goals, but have not rigorously tested the approach [45,56,57].

Controversy

There is ongoing controversy about the use of subliminal priming [42], including a level of "moral panic" [62]. Debates also continue over appropriate experiment methodology, statistical analysis and the replicability of effects [44,54,58]. There is also scepticism about how long these effects last [29], although recent evidence shows that even novel information can be retained for more than 20 minutes using these techniques and can subsequently influence conscious decision making [53].

Subliminal semantic priming in the lab

Recent advances in techniques to measure brain activity have provided evidence of semantic processing in response to masked primes [23]. Ocampo's recent lab-based work showed that users' free choices can be significantly influenced through subliminal priming of semantic representations [38]. A meta-analysis of masked priming showed that the average effect size for word primes was smaller than symbol or mixed primes, and that novel primes show a larger priming effect than repeat primes [60]. This indicates that semantic subliminal priming potentially has larger effects than stimulus-response priming.

STUDY

Although subliminal semantic priming effects have shown to impact people's choices in the lab, the technique has not been explored in a mobile deployment outside the lab. This study investigates the impact of subliminal semantic priming on users' choices when being deployed on a smartphone. The experiment is based directly on Ocampo's lab-based study (n=19) examining whether free-choice tasks –trials where there is no correct choice so participants are free to choose either of two alternatives– can be influenced by novel primes [38].

Our experiment addresses three research questions: RQ1, can people consciously recall concealed number primes on smartphones; RQ2, are these concealed number primes processed on a semantic level with different effects for novel and repeat primes; and RQ3, can these concealed number primes affect people's free choices, and is that effect different between repeat and novel primes. Our related hypotheses, in line with Ocampo [38], are:

- H1: the rate of participants correctly identifying concealed primes would be no better than chance. This would suggest that people could not see the concealed primes on smartphones (RQ1)
- H2: forced-choice (a) accuracy and (b) reaction times would be affected by prime congruence with no difference between novel and repeat primes. This would suggest that semantic processing of primes is as efficient in terms of accuracy and reaction time as stimulus-response processing (RQ2).
- H3: free-choice (a) selections would be in line with primes with no impact of novelty; and (b) reaction times for responses would be faster for responses in line with primes, with no differences for either novel and repeat primes. This would suggest that subliminal semantic priming can affect user's free choices in similar ways as stimulus-response priming (RQ3).

In our experiment we use *novel* and *repeat* primes, since repeat primes may have an effect via stimulus-response implicit mappings, while novel primes instead may only have an effect via semantic or meaningful cognitive processing.

Method

Participants

103 people (age: mean= 24.57 years, SD= 4.08; 38 women) participated in the experiment. We used a set of three same-batch Samsung Galaxy Nexus smartphones running Android 4.3. Android smartphones have a maximum frame rate of 60 frames-per-second, which is approximately ~16.67ms per frame, using vertical sync to align the software refresh rate with the display hardware refresh rate [28,44].

Procedure

Participants were approached on campus at the University of Birmingham and asked to participate in a number sorting task. They read a consent screen saying that the aim of the task was to categorise numbers as less than or more than 5, then completed a demographics questionnaire and a brief practice run.

Next, each participant completed 576 response task trials, 2/3 forced-choice tasks and 1/3 free-choice tasks, followed by 144 visibility trials. Table 1 summarises the experiment tasks, hypothesis and related research questions.

RQ, task & hypothesis	Research Question
RQ1 Visibility task H1	Can participants correctly identify primes?
RQ2 Forced-choice response task H2a	Do prime congruence and/or prime novelty affect accuracy in identifying the target?
RQ2 Forced-choice response task H2b	Do prime congruence and/or prime novelty affect reaction times?
RQ3 Free-choice response task H3a	Does prime novelty affect whether participants choose a response that matches the prime?
RQ3 Free-choice response task H3b	Does matching a prime and/or prime novelty affect reaction times?

Table 1. Tasks summary

Response tasks

A response task trial required looking at a smartphone screen with a display area where primes, masks and targets (a number or a symbol) appeared, and two buttons below, as shown in Figure 1. In contrast to the original study, where responses were recorded on a QWERTY keyboard, we used touchscreen buttons to gather responses. The left-hand button was marked with the less than symbol "<"; the right button was marked with the more than ">" symbol.

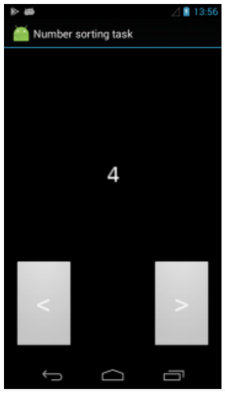

Figure 1. Experiment screenshot showing “4” as a target

In each trial, following a forward mask, a number prime, and a backward mask, a *target* appeared in the display area, as shown in Figure 2. Target stimuli could either be a number (*forced-choice* trials) or a “#” symbol (*free-choice* trials). If the *target* was a number, participants were asked to use the left or right button to indicate whether the number was greater or less than 5. We recorded reaction times as one outcome variable. Forced-choice trials in which participants correctly identified whether the target was greater or less than 5 were categorized as *correct* with others categorized as *incorrect*. This forms a binary accuracy outcome variable for the forced-choice trials analyses below.

If the target was the free-choice symbol “#”, participants were asked to respond freely using either button, avoiding the use of a set response scheme (e.g. “always left”). We recorded reaction times as one outcome variable. Trials in which participants chose the button that corresponded to the prime were categorized as agreeing, with others categorized as not agreeing. This forms a binary outcome variable for the free-choice trials analyses below.

Two-thirds of the 576 trials were forced-choice, with a number as the target. The remaining third were free-choice, with the free-choice symbol as the target. Half of the forced-choice trials had a *congruent* prime (prime and target were either both less than or both more than 5); half had an *incongruent* prime (prime and target were on the opposite side of 5, e.g. prime was more than 5 and target was less than 5).

In 50% of the response trials, a *novel* prime was used, i.e. a number that never appeared as a target. Numbers 2,3,7 and 8 appeared as *novel* primes only and never appeared as a *target*; numbers 1,4, 6 and 9 appeared as targets. In the remaining trials, *repeat* primes were used: numbers 1,4,6 and 9 appeared both as *target*s and *repeat* primes.

Masks were randomly generated: 30x30 pixel black backgrounds with multiple overlapping letters in white, with different forward and backward masks. Numbers appeared in white Verdana font size 20 on a 30x30 black background. This was the same colour combination as the Ocampo study [38]. We used this sans-serif font at size 20 because of evidence that sans-serif fonts and font sizes greater than 18pts are more accessible for people with dyslexia [48,49], and therefore suitable for a more accessible intervention should the technique be successful.

Participants were given 1.5 seconds to respond, and the app informed them if they got the answer wrong or they timed out. The prime appeared for 2 frames, approximately 34ms for the types of phones used in the experiment [44] and masks appeared for 4 frames, approximately 68ms, in line with Ocampo’s original experiment (masks ~70ms, primes ~33ms) [38]. Targets were displayed for ~203ms. The procedure is shown in Figure 2.

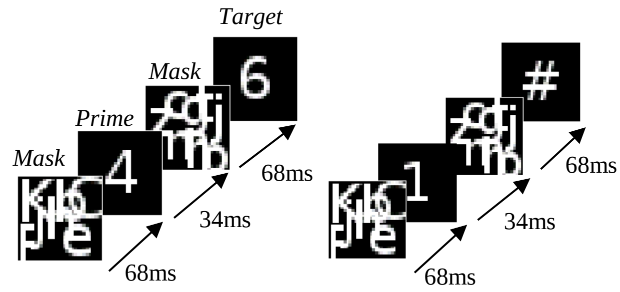

Figure 2. Subliminal priming procedure showing (left) an incongruent repeat forced-choice trial, and (right) a repeat free-choice trial

Visibility task

After completing the *response task* trials, participants were informed of the existence of the subliminal prime. They each then completed 144 *visibility trials* with the same stimulus proportions as the response task. In visibility trials, participants were asked to try and identify the *prime* by answering whether the prime itself, and not the target as in previous trials, was greater than or less than 5.

Task type	DV	IVs
Visibility (RQ1)	Response (binomial, more than or less than)	Prime value (binomial, more than or less than)
Forced-choice (RQ2)	Response time (continuous, ms)	Congruence (congruent or incongruent primes) Novelty (repeat or novel primes)
Forced-choice (RQ2)	Correct categorisation of target (binomial, correct or incorrect)	Congruence (congruent or incongruent primes) Novelty (repeat or novel primes)
Free-choice (RQ3)	Response time (continuous, ms)	Novelty (repeat or novel primes)
Free-choice (RQ3)	Agreement with prime (binomial, yes or no)	Novelty (repeat or novel primes)

Table 2. Experiment trials variables summary

Table 2 shows a summary of our independent variables (IVs) and dependent variables (DV) for the three trial types (visibility, forced-choice and free-choice).

Results

Data cleaning & summary

The final analysis included 72,720 trials from 101 participants after one participant was excluded because they recorded more than the 720 trials, and one was excluded because they did not complete all the trials. Trials where the participant timed out were then excluded (394 trials, 0.54%), as were trials where frame timing errors indicated a potential problem, i.e. a dropped frame of > 25ms was recorded (22 trials, 0.28%), in line with our previous work [44].

Data analysis

All statistical analysis was run using R, version 3.1.1 [46]. We constructed generalised linear mixed effects regression (GLMER) models using the lme4 package [10], with *p* values generated by the lmerTest package [33], to analyse our binary data outcomes and our reaction time data. This approach avoids possible incorrect outcomes from ANOVAs that aggregate the raw data into proportions in the case of binary data or means in the case of reaction times, and allow us to model for within-participant variation [32]. These models are starting to be adopted in HCI (e.g. [20,44]).

We followed Baayen & Milin to use a combination of model comparisons and outlier removal to refine our models [4]. Our models used deviation coding, since there is no clear baseline for our factors. Deviation coding means that the intercept of each model represents the grand mean, rather than the mean of the baseline factors.

There is some debate over the appropriate measurement of how well a GLMER model fits the data, i.e. how much variance in the data is explained by the model [19,36]. In line with Baayen & Milin [4], for non-binomial models we provide a simple pseudo-R-squared measure, R^2_{PS}, which estimates the correlation between fitted and observed values. For binomial models we provide marginal R squared, R^2_M, which estimates how much the model's fixed effects explain data variance, and conditional R squared, R^2_C, which estimate how much the model explains variance as a whole, from the MumIn package [8]. However, we also note that providing R^2 measures and *p* values is controversial [9]. We provide *p* values because it is a convention within HCI, and R^2 values to give some simple indication of model fit.

To ease interpretation, we also give estimated marginal values for the fixed parts of our models using the lsmeans R library [34].

Visibility task analysis (RQ1)

To examine whether people could consciously recall the concealed primes on smartphones (RQ1), we examined the data from 14,456 visibility trials conducted after participants had been informed of the nature of the experiment. The mean percentage of answers that agreed with the prime by participant was 50%, SD= 4.49%.

We removed 1 participant with an outlying same-response rate (143 trials, 1.0%). For the remaining 14,313 trials, we constructed a GLMER model to analyse whether the binomial participant response (more than or less than) could be predicted by the prime value (more than or less than), allowing for a random by-participant intercept. The model results (R^2_M=<.001, R^2_C=0.03) are shown in Table 3.

Fixed Effects	Estimate	SE	Wald z	p value
(Intercept)	0.10	0.03	3.44	<.001
Prime value	-0.02	0.02	-0.91	.36

Random Effects	SD
Participant (intercept)	0.30

Table 3. Visibility Task model results (H1)

The small statistically significant positive intercept indicates an overall pattern of participants selecting the "more than" response at a higher rate than "less than" response (*b*=0.10, *z*=3.44, *p*=<.001). However, there was no evidence that the prime value itself affected the likelihood of a particular response (*p* = .36). This supports our hypothesis H1.

Forced-choice task analysis (RQ2)

We analysed 38,450 forced-choice trials to address RQ2. We removed the data of 2 outlying participants who responded with the same response more than 65% of the time (759 trials, 1.97%). Descriptive statistics for the percentage of forced-choice trials that were correct (i.e. correctly categorised the target), grouped by prime congruence and prime novelty, are shown in Table 4.

Prime congruence	Prime novelty	Mean	SD
Congruent	Novel	87.55	8.31
	Repeat	88.29	7.83
Incongruent	Novel	87.16	8.47
	Repeat	87.03	7.60

Table 4. Forced-choice task correct trials (%) by prime congruence and prime novelty

Descriptive statistics for reaction time (RT) in milliseconds grouped by prime congruence (congruent, incongruent) and novelty of prime (repeat, novel) are shown in Table 5.

Prime congruence	Prime novelty	Mean	SD
Congruent	Novel	560.08	138.00
	Repeat	607.59	145.73
Incongruent	Novel	560.41	141.99
	Repeat	562.04	141.48

Table 5. Forced-choice task RT (ms) by prime congruence and prime novelty

To examine our hypothesis H2a that forced-choice accuracy, or correct categorisation of target, would be influenced by prime congruence (whether the prime and target were the same side of 5- *congruent*- or the opposite side of 5- *incongruent*), but not prime novelty, we constructed a logistic regression GLMER model analysing the effect of prime congruence (congruent or incongruent) and prime novelty (repeat or novel) on the correct categorisation of the target number displayed as higher or lower than 5 (correct or incorrect).

The model's random effects included a by-participant random intercept. The model (R^2_M <0.01, R^2_C = 0.16) results are shown in Table 6.

Fixed effects	Estimate	SE	Wald z	p value
(Intercept)	2.16	0.08	26.14	<.001
Congruence	0.04	0.02	2.50	.01
Novelty	0.02	0.02	0.98	.33
Congruence:Novelty	0.02	0.02	1.34	.18
Random Effects	**SD**			
Participant (intercept)	0.80			

Table 6. Forced-choice task categorisation results (H2a)

The results show that there is evidence of a small statistically significant main effect of congruence on the log odds of correct categorisation (*b*=0.04, *z*=2.50, *p*=.01), but no other main or interaction effects. This is in line with Ocampo's findings of a main effect of congruence and no other statistically significant effects on correct categorisation [38]. We found that when the prime was on the same side of 5 as the target number, (i.e. congruent primes) it improved the estimated probability of a correct categorisation of the number as above or below five by a very small amount, less than 1 percentage point (estimated marginal probability of correct categorisation of target for congruent = 90.0%, incongruent 89.3%).

To examine our hypothesis H2b that reaction times for responses would differ for congruence and novelty, we constructed a GLMER model to analyse reaction time data. A barplot of mean RTs for the forced-choice data is shown in Figure 3.

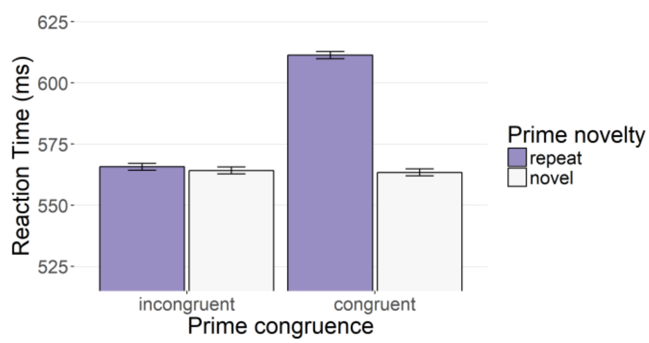

Figure 3. Forced-choice task barplot of trimmed mean RTs (ms) with 1SE bars (H2b)

Our model analysed the effect on reaction time of prime congruence (congruent or incongruent) and prime novelty (repeat or novel), including a by-participant random intercept as a random effect. We removed 1,020 trials (3.71%) based on model residuals. The model (R^2_{ps}= 0.26) results are shown in Table 7. The results indicate a statistically significant interaction between congruence and novelty (*b*=11.76, *SE*=0.49, *t*=24.00, *p* <.001).

Fixed effects	Estimate	SE	t	p value
(Intercept)	588.91	4.44	132.52	<.001
Congruence	12.11	0.49	24.66	<.001
Novelty	13.19	0.49	26.92	<.001
Congruence:Novelty	11.76	0.49	24.00	<.001
Random Effects	**SD**			
Participant (intercept)	0.80			
Residual	0.01			

Table 7. Forced-choice task reaction time analysis (H2b)

This effect is also shown in the model's estimated marginal mean RTs in Table 8. Congruent repeat primes (estimated RT=626ms) are estimated to have a slower response time than both congruent novel primes (576ms) and incongruent repeat primes (578ms).

	Prime novelty	
Prime congruence	Novel	Repeat
Congruent	576.1	626.0
Incongruent	575.4	578.2

Table 8. Estimated marginal mean forced-choice task RTs (ms) (H2b)

These results contrast with those from the lab for RTs: Ocampo found only a statistically significant main effect of congruence (*p* < .001, *d*=.96), where incongruent responses were slower, and no evidence of a statistically significant novelty main effect or congruence-novelty interaction [38]. Our results instead suggest that where primes contain pertinent information (congruent), people were slower in responding to repeat primes, compared to novel primes, although the estimated difference is small (~50ms). This is also shown in Figure 3: repeat prime RTs for congruent trials are higher (i.e. participant responses were slower) than other trials.

Free-choice task analysis (RQ3)

Next, we addressed RQ3. We hypothesised that people's free choices would be influenced by the concealed primes. We expected they would tend to respond to the free choice symbol in line with the value of the number prime shown, H3a.

We also hypothesised that there would be no main effect of prime novelty (novel or repeat) on reaction times to free-choice trials, H3b, i.e. that there would be no statistically significant difference between the influence of novel and repeat primes on reaction time, but there would be a main effect of agreement, where answers that match the prime result in faster reaction times. We examined the data from the free choice task and removed trials from 6 participants who responded with the same answer more than 80% of the time.

Descriptive statistics for free-choice trials for percentage of trials where participants selected the response that agreed with the prime, grouped by prime novelty, are shown in Table 9.

Prime novelty	Mean	SD
Novel	50.47	5.08
Repeat	53.32	7.69

Table 9. Free-choice agreement (%) by prime novelty (H3a)

Descriptive statistics for free-choice reaction time in milliseconds by prime novelty are shown in Table 10.

Prime novelty	Mean RT (ms)	SD
Novel	553.67	142.24
Repeat	553.91	142.10

Table 10. Free-choice reaction time (ms) by prime novelty (H3b)

To investigate whether the prime value and prime novelty affects participant free-choices as in hypothesis H3a, we used a logistic GLMER on the trimmed data to analyse the effect of the prime *value* (more than or less than 5) and prime *novelty* (novel or repeat) on participant response (whether they responded in the same direction as the prime, yes or no). The model included a by-participant random intercept as a random effect. The model (R^2_M = .01, R^2_C = .02) results are shown in Table 11.

Fixed effects	Estimate	SE	Wald z	p value
(Intercept)	-0.10	0.03	-3.68	<.001
Novelty	-0.07	0.02	-3.40	<.001
Value	0.36	0.03	11.85	<.001
Novelty:Value	0.03	0.03	0.90	.37
Random Effects		**SD**		
Participant (intercept)		0.14		

Table 11. Free-choice task agreement results (H3a)

The results show no statistically significant interaction between prime value and novelty (*p*=.37), but show both a statistically significant main effect of prime value (*z*=11.85, *p*=<.001), and a smaller statistically significant main effect of prime novelty (*z*=-3.40, *p*=.001) on the log odds of the participant agreeing with the prime. The statistically significant negative intercept (*p*<.001) indicates a trend towards participants not selecting an answer in line with the prime overall.

Considering the main effect of prime value, there is evidence that participants had a higher probability of agreeing with the prime when it was more than 5 (56.6%) than when it was less than 5 (47.6%). This may indicate some default tendency of participants to select the "more than 5" or right-hand answer overall.

In terms of prime novelty, our model indicates a statistically significant impact of novelty on agreement. There was a small increase in the estimated marginal probability of participants agreeing with the primed response in the repeat primes condition (53.6%), compared to the novel primes condition (50.7%). Although there is a smaller probability of agreement for novel primes, these probabilities are close to what would be expected by chance. These results contrast with those from the lab. Ocampo found a statistically significant overall positive trend for participants to select the primed response in the free-choice task, which we did not, but no evidence of the impact of novelty. Our results show little evidence that subliminal primes influenced participant choices, with the effect of novel semantically processed primes smaller than that of the repeat primes.

For hypothesis H3b, we constructed a GLMER model to analyse whether *prime novelty* (novel or repeat) and *agreement* (whether the free choice category chosen agreed with the number used as a prime or not) affected reaction time, including a by-participant random intercept as a random effect. We trimmed 573 trials (3.17%) based on model residuals. The results of the model (R^2_{PS} = .37) are shown in Table 12. As hypothesised, there was no evidence of a main effect of novelty (*p*=.87), but no evidence of an expected main effect of agreement (*p*=.07), and the results also showed a very small statistically significant interaction between novelty and agreement (*b*=1.55, *t=2.61*, *p*=.01)

Fixed effects	Estimate	SE	t	p value
(Intercept)	567.98	6.55	86.77	<.001
Novelty	-0.09	0.59	-0.16	.87
Agreement	1.10	0.59	1.84	.07
Novelty:Agreement	-1.55	0.60	-2.61	.01
Random effects	**SD**			
Participant (inter-	22.78			
Residual	0.01			

Table 12. Free-choice reaction time analysis results (H3b)

The estimated marginal mean RTs in Table 13 show that the model predicts a very small crossed interaction effect: for novel primes, responses that agree with the prime are estimated to be slower than disagreeing answers by less than 1ms, with the opposite pattern for repeat primes, where agreeing responses were faster by ~5ms.

	Prime novelty	
Agreement	Novel	Repeat
Response matches prime	568.3	565.4
Response does not match prime	567.4	570.7

Table 13. Estimated marginal mean free-choice RTs (ms) (H3b)

Again, our results contrast with those from the lab: Ocampo found no statistically significant main effect of novelty on free choice reaction time, but found a statistically significant main effect of agreement (faster RTs for agreement). No interaction significance was reported. Instead, we found that agreeing responses for repeat primes were very slightly faster (~3ms), compared to agreeing responses for novel primes. Again, the estimated effects are very small.

DISCUSSION

Our aim was to determine whether participant responses were based on some semantic processing of our concealed primes. Responses to *novel* primes indicate some level of semantic processing, whereas responses to *repeat* primes indicate some basic stimulus-response priming. Participants completed three sets of tasks; forced-choice trials in which they were shown a prime, then a target and asked to respond whether the target was greater than or less than 5 (with reaction time and correct-answer dependent variables); free-choice trials where they were shown a prime and a symbol target and asked to respond freely greater than or less than (with reaction time and agreement-with-prime dependent variables); and finally visibility trials after the presence of primes had been revealed where they were asked to respond whether the *prime*, not the target, was greater than or less than 5 (with a binomial answer value dependent variable).

Our results are summarised in Table 14. Although the results indicate some different responses for novel and repeat primes, suggesting some differences between semantic and stimulus-response processing, note that all our result sizes were small, and our models had low R^2 estimates of model fit, with relatively high participant random effects.

Task and hypothesis	Result
Visibility task H1	No evidence of visibility (no evidence of impact of prime value on selection).
Forced-choice task H2a	No evidence for different impact of semantic vs stimulus-response processing on accuracy (no evidence of impact of prime novelty). Evidence of very slightly improved accuracy (<1 percentage point) for congruent primes.
Forced-choice task H2b	Evidence of slightly slower stimulus-response processing than semantic processing where primes contain correct information about the target (congruent repeat primes estimated to have a ~50ms slower reaction time than congruent novel primes).
Free-choice task H3a	Evidence that stimulus-response processing very slightly improves agreement compared to semantic processing (repeat primes estimated to improve probability of answers matching the prime compared to novel primes by ~3 percentage points to 53.6%).
Free-choice task H3b	Evidence that semantic processing is very slightly slower than stimulus-response processing for answers matching the prime (responses to novel primes estimated to be ~3ms slower than repeat primes).

Table 14. Results summary

The first research question was whether we can conceal number primes. From the visibility task (H1), we found a small statistically significant overall tendency for participants to select the "more than" answer at a higher rate than "less than" answer, but no evidence of a statistically significant effect according to prime value (more than or less than 5). Therefore, there is no evidence to suggest that the primes were visible. This contrasts positively with the evidence we found in our previous experiments in subliminal priming when using different sorts of primes (polygons, words and photos) that people could detect the primes to a certain extent [44].

The second question was whether congruent masked primes (i.e. primes that semantically agree with the target) increased accuracy and reduced reaction time, and whether this effect differed between repeat and novel primes. Forced-choice categorisation results (H2a) showed a very small statistically significant impact of congruence, where congruent primes slightly improved the probability of correct categorisation of target by <1 percentage point, but no evidence of a statistically significant impact of prime novelty. The results from the forced-response task reaction times (H2b) showed evidence of a statistically significant interaction between congruence and novelty, where congruent repeat primes tended to result in slightly slower reaction times (~50ms) than other conditions. Therefore, in terms of accuracy, there is little evidence of effective subliminal priming using congruent primes. In terms of reaction time, there is evidence that congruent repeat primes, which indicate some level of stimulus-response processing, slow down reactions very slightly.

The third research question was whether the primes affected people's free-choices. Where participants freely chose the answer that matched the prime (H3a), we found a statistically significant main effect of both prime novelty and prime value on participant responses. Repeat primes statistically significantly improved the probability of answers matching the prime compared to novel primes by ~3 percentage points to 53.6%. This is some evidence that repeat primes may influence free choice to a small extent. However, the evidence is mixed since participants also tended to select one answer (the "more than" answer) rather than the other (the "less than" answer), with a higher estimated selection probability of 56.6%. This may indicate that subliminal priming is insufficient to overcome a user tendency to default to one answer in situations of arbitrary selection such as the free-choice task.

In terms of free-choice reaction times (H3b), there was an interaction effect of *prime novelty* and *agreement* (i.e. answers that matched the prime). The results show that when the answer agreed with the prime, novel primes tended to result in a very slightly slower response (~3ms) than repeat primes. This suggests that semantic processing of novel primes –i.e. so that the participant processed the semantic information in the prime to agree with it– slows reaction times to small extent, compared to stimulus-response processing acquired from the repeat primes.

Overall, on the definition of subliminal priming of an indirect effect (our forced-choice and free-choice tasks) without a direct effect (our visibility task), there is some evidence of a very small subliminal priming impact on user choice. Our visibility task showed no evidence of an impact of prime value on selection, while our forced-choice task showed a very small increase in accuracy (less than 1%) where targets were in line with primes.

The evidence also shows that the impact of *semantic* subliminal processing, activated by novel primes, is inconsistent across free- and forced-choice trials. In free-choice trials, novel primes are estimated to have a smaller impact on correct selection than repeat primes. Prime novelty also impacted on reaction time in the free-choice task, with repeat primes decreasing correct reaction times compared to novel primes very slightly by ~3ms. Within the forced-choice trials, where primes were congruent with the target, repeat primes increased reaction times slightly by ~50ms. There was no evidence of an impact of prime novelty on correctness in forced-choice trials.

Overall, caution is advised in applying the technique, since the size of the effects is very small. The evidence shows that using subliminal primes to improve interaction efficiency on smartphones is likely to make little difference. Likewise, given the lack of evidence of any strong semantic priming effects, there is no support for the application of semantic priming in behaviour change applications such as the use of subliminal goal priming of short word phrases. This is consistent with our lack of results from attempts to use subliminal goal priming in-the-wild [44].

Our results differed from the original lab experiment [38] in several respects. For visibility, RQ1, we found no evidence of visibility, while the lab study found that participants' ability to discriminate primes did differ from zero. For free-choice trials, Ocampo found a statistically significant overall positive trend for participants to select the primed response, but no evidence of the impact of novelty. By contrast, we found an overall negative trend for participants to select the primed response in free choice trials, with small statistically significant main effects of both *novelty* and *value* (i.e. whether the answer was "more than" or "less than"). Ocampo did not report value results, but our results indicates some potential default preference for responding in a particular direction (towards "more than") on mobile devices.

For forced-choice trials, Ocampo found a statistically significant main effect of agreement (faster RTs for agreement). Instead, we found an interaction effect between novelty and agreement: agreeing responses for repeat primes were slower, compared to agreeing responses for novel primes.

The differences are interesting: our analysis included 101 participants compared to Ocampo's 19. Our results with a larger sample indicate little point in implementing practical applications of subliminal priming, at least of numbers, on smartphones. Ocampo's study provided some evidence that in controlled lab conditions, apparently free choices can be influenced by subliminal novel primes. Our larger sample in a noisier environment with a similar experiment on smartphones found some evidence that free-choices are influenced differently to a small extent by novel and repeat primes, but the rates of selecting the option that matches the prime are close to chance (novel, 50.7%; repeat, 53.6%), the impact of novel is smaller than that of repeat primes, and our measures of model fit are very low. In all, despite some statistically significant differences between the effects of novel and repeat primes, the effects are very small. This may, in part, reflect a general tendency for less-controlled participants to perform tasks faster with less accuracy than lab participants [27], although our visiblity tasks results indicate that some pre-existing response behaviours (e.g. to press the right-hand button) may have also influenced the experiment.

In short, our research provides further evidence that subliminal priming is feasible on smartphones but is of limited practical use.

Limitations

As with all reaction time data, our data was noisy [4] and some model residuals still indicated some departure from normality. Our R^2 values of model fit indicate that the models were overall poor estimators of the explained variance, particularly for the visibility task. The semi-controlled nature of the experiment meant that participants could be distracted by environmental factors beyond our control. We did not collect data on the experimental context e.g. by monitoring background noise using the microphone [13]. Further, the experiment used our experiment phones, rather than participants' own equipment: a true in-the-wild experiment may yield different results. Nevertheless, we note evidence that response times for smartphone experiments both in-the-lab and in-the-wild are similar [26].

Our prime sizes also differed slightly from the original experiment, which may have affected the results. The original experiment displayed primes at approximately 10mm high on a 1024x768 monitor, although participant distance from the monitor was not given. Our experiment displayed primes at a slightly larger size of 20 pts / 50px / 18mm high on our 720x1280 smartphone screens due to accessibility issues.

FUTURE RESEARCH

Re-running the experiment on the same devices in controlled conditions would help to disambiguate the effects of running the experiment on smartphones outside the lab. Experimenting with a wider variety of stimuli beyond numbers is important to understand whether the very small effects of semantic priming using numbers are generalisable. Using short words as primes is important in the behaviour-change example of subliminal goal priming [44]. Future work should also include experiments to determine whether larger effects might be obtained by using supraliminal (i.e. visible) priming on smartphones.

The future of subliminal priming?

Our research, along with other studies [41,44,60], found evidence that the effectiveness of subliminal priming is mixed. Yet as HCI research moves beyond mobile in the next 20 years, there are opportunities to explore priming more broadly, focusing on three key themes: pervasiveness; tailoring; and ethics.

Pervasive adaptive priming

As technology embeds ever more pervasively into people's lives, it is possible that increasing numbers of intervention points alongside more powerful and increasingly accurate sensor technology could overcome some of the current limitations through opportunistic priming. The technology could form an ambient persuasive network capable of delivering priming without increasing user cognitive load [3,30]. Such a distributed network tracking a person's actions and reactions provides multiple mobile opportunities for intervention.

Tailoring

Adaptive systems for individual preferences and cognitive abilities is not a new HCI theme [39]. However, the convergence of more powerful distributed sensors and processors will bring further opportunities for systems to adapt themselves to user preferences, e.g. improved ability to predict a user's next technology interaction [40], and to select a context-appropriate priming intervention such as an incidental interaction [25].

Such opportunistic priming could be either subliminal or supraliminal, with systems able to use feedback about the individual user's state to infer the most appropriate mode to avoid cognitive overload and/or irritation. Future priming systems could switch between liminal modes depending on an analysis of likelihood of success vs. risks of disruption or irritation [40], likely driven by a machine learning engine [16] tailored to the target individual. Such extreme tailoring, particularly where primes are presented subliminally, would raise issues of intelligibility [12]. If users cannot consciously recall their primes, how can they determine whether the system is acting appropriately? This relates both to system accuracy, and our third key theme, ethics.

Ethics

We expect ongoing tension between advertising-funded advances in pervasive technology that can deliver priming and people's best interests. The idea of a constantly-on system monitoring people for vulnerable persuasive intervention opportunities is disquieting if the system goals are ultimately commercial and not utilitarian. This is particularly the case if the interventions are delivered subliminally, with no opportunity for the individual to consciously resist. Yet developing utilitarian technology requires either some form of "libertarian paternalism" as suggested by nudge theory [59] to define what is in people's best interests, or giving power to individuals to define their own goals.

CONCLUSION

Improving the efficiency of human-computer interaction requires an appropriate understanding of human information processing [47]. In mobile HCI, this processing also takes place in high-distraction environments. We have found little evidence that subliminal priming is an appropriate technique on mobile devices to encourage efficiency in interaction or cognitive activation: attempts to transfer information subliminally does not improve accuracy or reaction time to any great extent.

HCI research has yet to establish a stable, practical application for the technique, particularly in the behaviour change domain. As sensing and processing technology improves over the next 20 years to provide pervasive, distributed, multiple opportunities for intervention, researchers may be able to establish a more effective means of priming people to achieve cognitive activation for behaviour change.

The small effects that differ across conditions may be some comfort to researchers concerned about future encroachment into our nonconscious processes by increasingly pervasive technology-driven interventions, Nevertheless, larger more stable effects could potentially emerge from predicted future research into extreme tailoring and much more pervasive subliminal and supraliminal priming. The onus is on us as HCI researchers to hold the ethics line in the face of commercial pressures to exploit nonconscious information processing.

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