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Visual Uncertainty in Serial Dependence: Facing Noise

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Title
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SwedishTitle
Visuell Osäkerhet vid Seriellt Beroende: Effekt av Brus

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Abstract

Empirical evidence suggests that the visual system uses prior visual information to predict the future state of the world. This is believed to occur through an information integration mechanism known as serial dependence. Current perceptions are influenced by prior visual information in order to create perceptual continuity in an everchanging noisy environment. Serial dependence has been found to occur for both low-level stimuli features (e.g., numerosity, orientation) and high-level stimuli like faces. Recent evidence indicates that serial dependence for low-level stimuli is affected by current stimulus reliability. When current stimuli are low in reliability, the perceptual influence from previously viewed stimuli is stronger. However, it is not clear whether stimulus reliability also affects serial dependence for high-level stimuli like faces. Faces are highly complex stimuli which are processed differently from other objects. Additionally, face perception is suggested to be especially vulnerable to external visual noise. Here, I used regular and visually degraded face stimuli to investigate whether serial dependence for faces is affected by stimulus reliability. The results showed that previously viewed degraded faces did not have a very strong influence on perceptions of currently viewed regular faces. In contrast, when currently viewed faces were degraded, the perceptual influence from previously viewed regular faces was rather strong. Surprisingly, there was a quite strong perceptual influence from previously viewed faces on currently viewed faces when both faces were degraded. This could mean that the effect of stimulus reliability in serial dependence for faces is not due to encoding disabilities, but rather a perceptual choice.

Keywords

Serial dependence, information integration, predictions, face perception, noise, stimulus reliability, visual uncertainty

Visual Uncertainty in Serial Dependence: Facing Noise

”Everything we see is a perspective, not the truth” (Marcus Aurelius, 121-180 CE)

The domain of perceptual science is not new to the idea of considering the human brain as a prediction machine capable of taking advantage of statistical regularities to make sense of the surrounding environment. This approach dates back to the 20th century when the German scientist and philosopher Hermann von Helmholtz (1925) introduced the idea of perception as unconscious inference. Helmholtz theory has since been extended to Friston’s (2009) free energy principle along with probabilistic theories of perception as Bayesian inference and predictive coding accounts to provide an explanation for how the human perceptual system operates (Cicchini, Anobile & Burr, 2014; Dayan, Hinton, Neal & Zemel, 1995; Kersten, Mamassian & Yuille, 2004). There is no lack of empirical literature suggesting that our perceptions regarding the environment are partly due to prior knowledge involving statistical regularities of our surroundings, which in turn is used to predict future sensory information (Friston, Adams, Perrinet & Breakspear, 2012; St. John-Saaltink, Kok, Lau & de Lange, 2016; Yuille & Kersten, 2006).

Whenever we turn our heads, move, or only when shifting our gaze, the world around us change. Despite these visual disturbances, all common sources of visual noise, perceptions regarding our environment (e.g., people, objects, scenes) are experienced as very stable. In order to smooth out our perceptual experiences and create stability in this everchanging noisy environment, prior research suggests that visual perception operates through a predictive mechanism known as *serial dependence* (Kiyonaga, Scimeca, Bliss & Whitney, 2017). Common to other sensory systems, serial dependence attempts to create perceptual stability by exploiting prior stimuli statistics in order to predict the future state of the world. This takes place by integrating previous and current visual information which results in a final prediction where current perceptions are partly influenced by previous visual information (Fischer & Whitney, 2014; Srinivasan, Laughlin & Dubs, 1982). Thus, current perceptions would not mirror the actual truth about the environment, they would rather be a combination between what one previously saw and what one sees in the present moment.

This integration process extends to recently viewed stimuli, as far as 15 s back in time. Within this timeframe termed as the *continuity field*, currently viewed objects look more similar to previously viewed objects than they actually are. Serial dependence would thus induce a positive after-effect from previously viewed objects on current perceptions within the continuity field (Kiyonaga et al., 2017). This object continuity is only present with shorter stimulus presentations. Stimulus presentations exceeding 4-5 s will induce the opposite effect where currently viewed stimuli are perceived as more different to previously viewed stimuli. As opposed to serial dependence, this is known as repulsive or negative after-effects (Fischer & Whitney, 2014; Kok, Taubert, Van der Burg, Rhodes & Alais, 2017).

The assumption that the past contains valid information to predict the future might seem problematic. Current perceptions free from previous influences would clearly give a more accurate description of the environment. However, serial dependence does not integrate all available visual information. This predictive mechanism is dependent on to what extent previous stimuli and current stimuli are separated in space, time, and how similar they are in features. When the difference between previous and current visual information surpass a certain magnitude, serial dependence will not occur. This predictive mechanism is also modulated by attention, unattended previous stimuli would thus not influence current perceptions (Kiyonaga et al, 2017). Serial dependence as an information integration mechanism is also assumed to be advantageous on a neural level. Rather than reprocessing current information on a moment to moment basis, recycling of previous visual information could be effective in saving neural resources and reduce cortical processing (Manassi, Liberman, Kosovicheva, Zhang & Whitney, 2018). Operating to promote object continuity, serial dependence has the ability to reduce change detection and increase change blindness for stimuli high in similarity by making similar objects and features look more alike within the continuity field (Liberman, Zhang & Whitney, 2016).

By allowing the influence from previous visual information on current perceptions, serial dependence might intuitively be seen as a misperception. Despite this, researchers suggests that serial dependence should be thought of as an adaptive mechanism, aiming to enhance perceptual stability and create order out of chaos in an environment filled with visual disturbances stemming from different sources of noise (Fischer & Whitney, 2014). A recent interest in the effect of serial dependence has led to a considerable amount of empirical evidence, suggesting that this dependency effect can occur for a variety of objects and features, such as orientation, object identity during occlusion, numerosity, facial expressions, attractiveness, visual variance, and faces (Cicchini et al., 2014; Fischer & Whitney, 2014; Kiyonaga et al, 2017; Kok et al, 2017; Liberman, Fischer & Whitney, 2014; Liberman, Zhang & Whitney, 2016; Manassi, Liberman, Chaney & Whitney, 2017; Suaréz-Pinilla, Seth & Roseboom, 2018).

Serial dependence functions as a ”smoothing operator” in the presence of visual noise in order to keep the environment predictable and stable within the continuity field (Liberman et al., 2016). External visual noise causes a certain loss in how much visual information that can be consciously attended to and makes perceptions of the surrounding environment more uncertain and unpredictable. In the presence of external noise, the variability in visual stimuli is greater and causes a higher level of uncertainty (Hulme & Zeki, 2007). In order to make predictions about the current state of the world some evidence needs to be collected. When faced with visual uncertainty, the brain needs to take the noisy sensory information into account in perceptual decision making. To predict the identity, or detection of an object through snowflakes in the middle of a blizzard would be a lot harder compared to when the same object is viewed on a bright sunny day.

Visual perception is goal oriented and reliant on fast and efficient information processing. External noise prolongs the time for identification and detection, and the visual information integrated from available sources contains information both regarding the presence and the absence of an object. Thus, external noise makes visual information much more unreliable and has a negative impact on perceptual decision making (Bitzer & Kiebel, 2015; Quétard et al., 2016). When attempting to predict the current state of the world by integrating visual information, current predictions depends on the reliability of the visual evidence that is collected. When current visual information is more unreliable (i.e., uncertain) compared to previous information, previous visual information will be more influential on the most likely predicted perceptual outcome (Yuille & Kersten, 2006). If the goal is to reduce noise and enhance perceptual stability without being overly concerned about the truth, this type of information integration would be most effective.

Cicchini, Mikellidou, and Burr (2018) found that the level of serial dependence and the influence from previous visual information varied depending on the reliability of currently viewed stimuli. By varying the spatial frequency and orientation for Gabor gratings (i.e, sinusoidal gratings frequently used to study visual perception) they investigated whether serial dependence is stronger when previously viewed stimuli are considered more reliable compared to currently viewed stimuli. The results supported the notion that integrating information from different sources can be beneficial when sensory representations are contaminated by external noise. Thus, combining information from currently and previously viewed stimuli would reduce the overall level of noise and create more stable representations (Alais & Burr, 2004; Kersten et al., 2004). Combined with previous research showing that low numerosities, considered as high in reliability since they are easy to remember, were not as sensitive to serial dependence effects compared to higher numerosities indicates that serial dependence changes as a function of stimulus reliability (Cicchini et al., 2014; Cicchini et al. 2018). When visual information about current perceptions are uncertain due to higher variability, the influence from previous visual information is stronger. Taken together, these results suggests that serial dependence could operate as an important mechanism in maintaining perceptual stability by attempting to reduce enhanced stimulus uncertainty in the presence of external visual noise.

In the above mentioned studies, the authors used numerosities and low-level artificial experimental stimuli (i.e., Gabor gratings). Artificial stimuli might not generalize to natural stimuli encountered in real life very well because of their low complexity (Manassi et al., 2017, Yuille & Kersten, 2006). Faces on the other hand are highly complex stimuli which most of us are exposed to on a daily basis, and there is evidence suggesting that serial dependence does occur even for such high-level stimuli (Kok et al., 2017; Liberman et al., 2014).

To investigate if serial dependence occurs for faces, Liberman et al. (2014) conducted an experiment using a sequence of 148 morphed images between three female faces. Subjects were asked to match a randomly presented target face by adjusting another randomly presented face from the morphed image sequence until they believed it too look similar to the previously presented target face. The authors found that perceptions of currently viewed target faces were influenced by previously viewed target faces presented up to 7 s earlier. By conducting three more experiments the authors concluded that this perceptual influence from previously viewed faces on currently viewed faces also held for faces presented across different viewpoints. After controlling for response biases by choosing to leave responding out in 50 % of trials, the authors could conclude that the serial dependence effect for faces was genuine and not due to an influence from previous responses on current responses. Kok et al. (2017) also used faces as experimental stimuli when investigating if perceived attraction for previously viewed faces had an influence on currently presented faces. Results showed that serial dependence for facial attractiveness did occur. Currently viewed faces were rated as more attractive when following attractive faces rather than unattractive faces. Combined, the results from these two studies would suggest that serial dependence not only occurs for object perception, but can also operate at an identity level in face perception.

It seems well established that faces are processed differently from other objects (Chen, McBain & Norton, 2015). That faces are processed in a holistic manner (i.e., spatial relationships are calculated throughout the face), rather than by featural processing seems to be the most established view in the scientific domain of face perception. To be able to discriminate faces from other objects and detect spatially relevant information (i.e., two eyes above a nose above a mouth) holistic processing is assumed to be necessary (Paras & Webster, 2013). While some research claims that the addition of external noise to a face can disrupt normal face processing, thereby forcing individuals to use alternative face processing strategies, other research claims that external noise causes a greater strain on face processing strategies normally used for face perception since local facial features gets more difficult to perceive (Duchaine & Nakayama, 2006; Macke & Wichmann, 2010).

The same amount of external visual noise has been found to have a greater impact on face perception compared to other objects (e.g., cars), suggesting that face perception might be more vulnerable to external visual noise compared to non-face related objects (Chen et al., 2015). Research on healthy controls and individuals diagnosed with *prosopagnosia* (i.e., the inability to recognize faces) has also showed that healthy controls were more sensitive to the addition of external noise to face images compared to individuals with prosopagnosia. The presence of external noise in face images might not just affect the ability to perceive facial features, but could also have an impact on surface reflectance and the ability to obtain the three-dimensional shape of the face (Corrow, Albonico & Barton, 2018). This combined suggests that face perception might be especially vulnerable to external visual noise and thus would be highly affected by stimulus reliability.

So far, research suggests that the presence of external visual noise does reduce stimulus reliability, which is crucial in perceptual decision making (Bitzer & Kiebel, 2015; Hulme & Zeki, 2007; Quétard et al., 2016), and that stimulus reliability does seem to affect serial dependence for orientation perception and numerosity (Cicchini et al, 2014; Cicchini et al., 2018). Additionally, the evidence also seems to indicate that faces are likely to be susceptible to serial dependence (Kok et al, 2017; Liberman et al., 2014), and point in the direction of a specific vulnerability to external visual noise for face perception (Chen et al., 2015; Corrow et al., 2018; Duchaine & Nakayama, 2006; Macke & Wichmann, 2010). What is currently missing from the literature is whether stimulus reliability affects serial dependence for naturalistic stimuli like faces. This opens up to the question: how does the presence of external visual noise affect serial dependence for faces?

If faces are specifically sensitive to external visual noise, degrading a face image by adding external noise should make it less reliable (i.e., uncertain) and serial dependence would be expected to vary depending on whether the previous or currently viewed face is degraded. When the currently viewed face is degraded and the previously viewed face is regular (i.e., without noise), the effect of serial dependence would be expected to be stronger. In a reversed condition, where the currently viewed face is regular and the previously viewed face is degraded, serial dependence would be expected to be weak or even nonexistent. Similarly, a weak or nonexistent effect of serial dependence would also be expected when both the current and previously viewed face is degraded. With the following experiment, I investigated whether serial dependence for faces is affected by stimulus reliability in terms of external visual noise. To provide a baseline and get further evidence for serial dependence for faces, I also included a condition similar to experiment 1 in Liberman et al. (2014) where both the previous and currently viewed faces were regular.

Method

Subjects

A total of 8 subjects (1 female) participated in this experiment. Age ranged from 23 to 40 years (*M* = 27, *SD* = 5.8). One subject chose to terminate before the experiment was completed and left only partial data, and a second subject probably misunderstood the task assignment. Therefore, data from these two subjects were excluded. This resulted in a total of 6 subjects for this experiment. All subjects had normal or corrected-to-normal vision. All subjects were naive as to the purpose of the experiment and were only informed that they would be participating in a study investigating visual perception. They were also informed that their participation was voluntary and that they could choose to terminate at any time of choice. All subjects were offered sweets for their participation. Subject sample size was chosen based on previous research using a similar paradigm when investigating serial dependence for faces where sample sizes were between 3 to 6 subjects (Liberman et al., 2014). All subjects were undergraduate students from courses in IT and biomedical analysis recruited from Kristianstad University.

Stimuli

The experiment was conducted in the laboratory at Kristianstad University. Subjects viewed stimuli on a 24 inch Dell computer screen at a distance of approximately 50 cm. All stimuli were presented in the center of the screen. The stimuli consisted of a grayscale morphed image continuum between 3 front-facing male faces with neutral facial expressions downloaded from the Face Research Lab London Set (DeBruine & Jones, 2017). All images were cropped by an oval mask, leaving only the faces visible and excluding the hairlines. A 142 face morph continuum was created in Webmorph (www.webmorph.org) which generated a set of 47 morphed face images between each of the three faces. Images of the three original faces and example faces from the morphed continuum are displayed in Figure 1 in the Appendix. To create visual uncertainty, degraded faces were presented with zero-mean Gaussian noise with a level of 0.3. All face images were presented on the screen against a gray background. The experiment was programmed in MATLAB (The MathWorks, Natick, MA).

Procedure

For this experiment a similar paradigm to experiment 1 in Liberman et al. (2014) was used. Subjects were asked to read the instructions for the experimental task on the screen, and when ready, press the ”SPACE” key to begin the experiment. At first the subjects were presented with a random target face, this face was either regular or degraded by zero-mean Gaussian noise. The target face was presented for 750 ms for each trial. The target face was followed by a 1000 ms noise mask of black and white pixels to reduce after image effects. Following the noise mask and prior to the response, a 250 ms fixation cross appeared on the screen. A method of adjustment (MOA) task was used to investigate whether the subjects were able to identify the randomly presented target faces, with or without external visual noise. A random adjustment face was presented on the screen. Subjects used left and right arrow buttons to change the adjustment face until they believed it to look similar to the target face. ”Target face” indicates the face that subjects were asked to match,” adjustment face” means the randomly presented face used as the starting point in the continuum when trying to match the target face. ”Response face” is the face that subjects chose as the one most similar to the target face. Time taken to adjust and respond was self-paced. There were two randomized trial types in the experiment: 50 % of trials where target faces were degraded and 50 % of trials where target faces were regular. All adjustment and response faces were presented as regular in all trials (100 %).

This experimental design allowed me to investigate four conditions: current target face regular – previous target face regular (RR), current target face degraded – previous target face regular (DR), current target face regular – previous target face degraded (RD), and current target face degraded – previous target face degraded (DD) (Table 1). Since target faces were randomly presented, each condition was expected to appear in 25 % of 284 trials. To determine if perception of a currently presented target face was influenced by the target face from the previous trial, subjects identification errors on the MOA were measured. Responses were registered as the numerical value of the response face along the continuum, values ranging from 1 to 142. Six subjects completed one block each, containing 284 trials. The experiment lasted between 1 h 15 min to 1 h 30 min. Figure 1 displays one trial sequence with a degraded target face.

Table 1.

Experimental conditions and abbreviations

Experimental conditions	Abbreviations
Current target face regular – previous target face regular	RR
Current target face degraded – previous target face regular	DR
Current target face regular – previous target face degraded	RD
Current target face degraded – previous target face degraded	DD

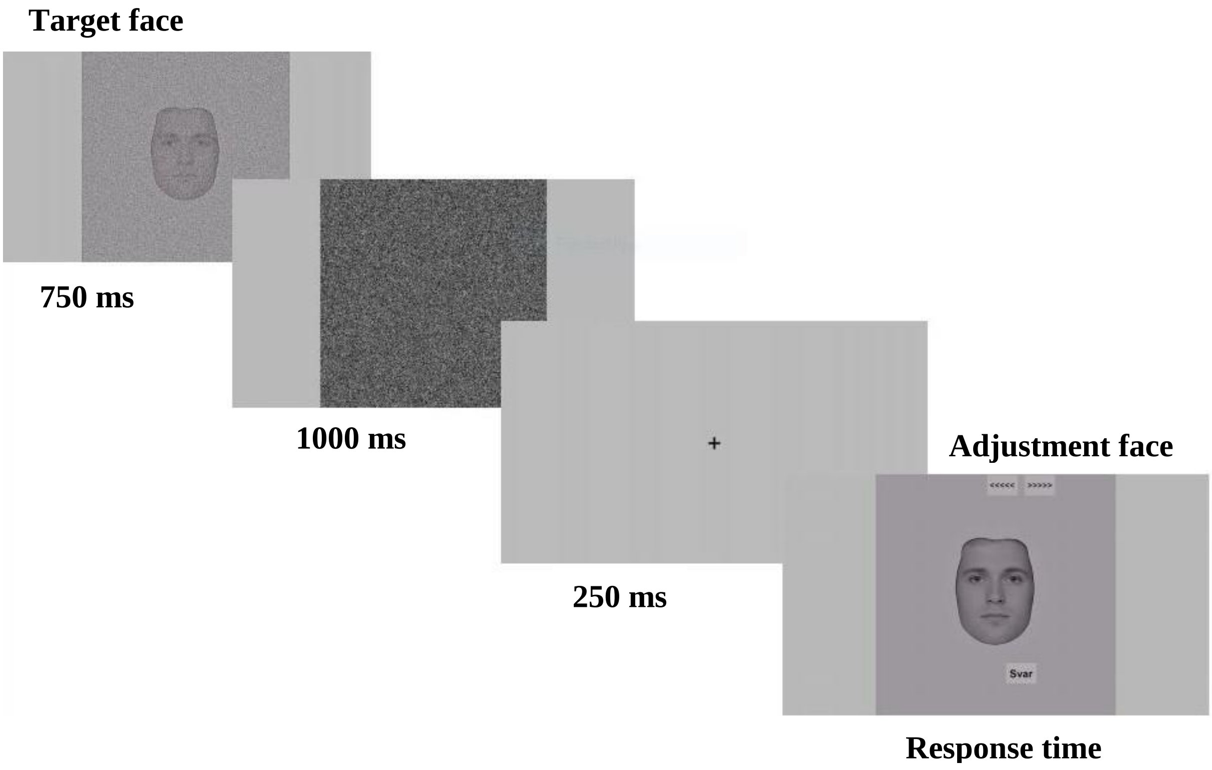

Figure 1. Trial sequence. A randomly selected target face was presented for 750 ms for each trial, the target face was followed by a 1000 ms noise mask of black and white pixels to reduce after-image effects. After the noise mask and prior to the response, a 250 ms fixation cross appeared, this was followed by a randomly selected adjustment face. Subjects used left and right arrow buttons to change the adjustment face until they believed it to look similar to the target face, the response face was submitted by pressing the ”svar” button. The target face was presented as degraded in 50 % of trials and as regular in 50 % of trials, the adjustment and response face was presented as regular in all trials.

Statistical analysis

Each subject's data were analysed individually. Identification errors were calculated as the shortest distance in morph steps along the morphed continuum between the target face and the response face. Since the continuum was in the shape of a wheel (Figure 1; see Appendix), the shortest distance in morph steps is the same as the number of morphed images between two faces taking the closest route between them in the wheel. Thus, a high identification error would mean that the selected response face is further away from the target face. Identification errors were then compared to the difference in target faces between the current trial and the previous trial (*n – 1*). This was calculated as the shortest distance in morph steps between target faces from previous trials and target faces from current trials. If serial dependence would occur, responses in current trials would be expected to be pulled in the direction of target faces from previous trials.

When identification errors are plotted against differences between current and previous target faces it results in the sort of scatterplot displayed in Figure 2. Here, errors in one direction corresponds to differences between current and previous target faces in the same direction. The curve represented by the solid line in Figure 2 captures the degree of serial dependence (i.e., to what degree a subject's perception of target faces viewed in current trials was influenced by target faces viewed in previous trials). This is represented by the half-amplitude (i.e. the highest point in the curve from peak to zero). This type of curve is known as the first derivative-of-Gaussian (DoG). The DoG curve displayed in Figure 2 is an example from the RR condition for subject 6.

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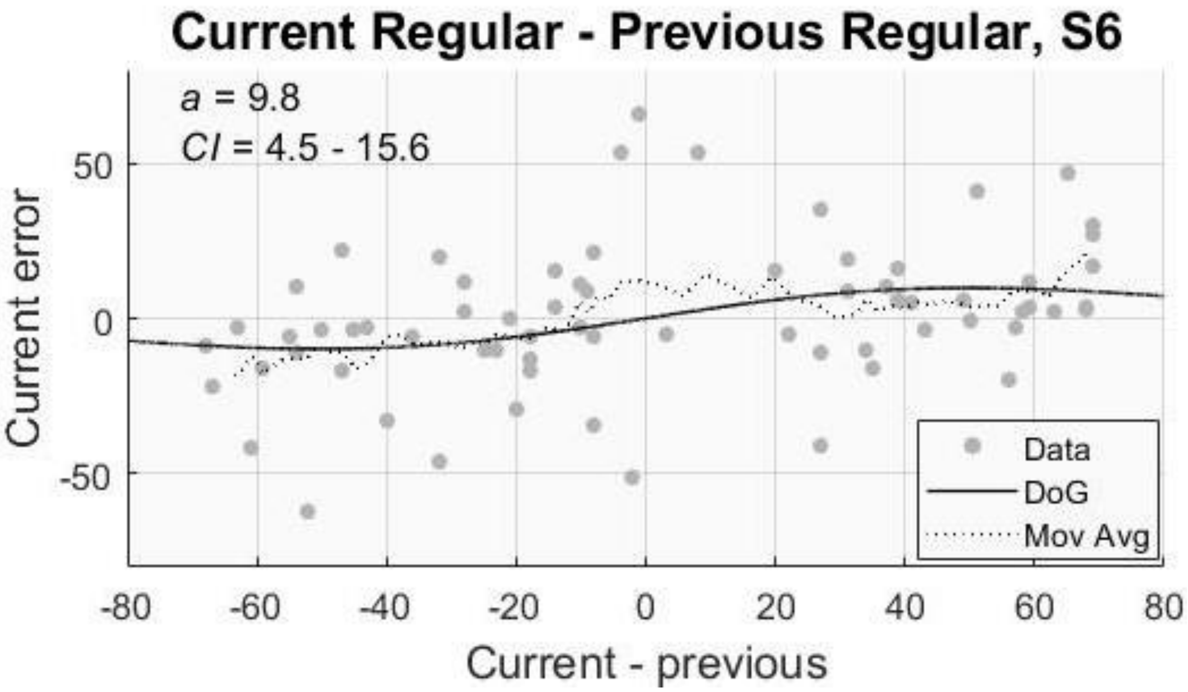

Figure 2. Derivative-of-Gaussian (DoG) curve for subject 6 from the RR condition. Data points represents performance for each trial. The vertical axis represents identification errors in morph steps between the target face and the response face. The horisontal axis represents the distance in morph steps between the current trial's target face and the previous trial's target face (*n – 1*). The moving average is displayed by the dashed line and the derivative-of-Gaussian (DoG) as the solid line. *a* is the half-amplitude (i.e. the highest point in the curve from peak to zero representing to what degree a subject's perception of target faces in current trials was influenced by target faces from previous trials) of serial dependence and CI is the 95 % confidence interval for *a*.

Here, a derivative-of-Gaussian curve was fitted separately for each condition to each subject's data using constrained nonlinear minimization of the residual sum of squares. The DoG was fitted of the form: $y = f(x)\mu\sigma * x * alpha$, where $f(x)$ is a normal probability density function (PDF) with mean μ and standard deviation σ. y stands for each trial's identification error (i.e., the shortest distance in morph steps between the response face and the target face), x is the shortest distance in morph steps along the continuum between the target face in the current trial and the target face in the previous trial (*n – 1*). *alpha* controls the amplitude of the curve and when multiplied by $f(x)*x$ (i.e., the first derivative of the Gaussian function) it affects the height of the curve. The width of the curve is controlled by σ (i.e., the standard deviation of the Gaussian distribution). The half-amplitude from each subject's data was used as a measurement for serial dependence. If a subject's perception of target faces in current trials was repelled away from, or not influenced by target faces in previous trials, then the half-amplitude of the best fitting DoG curve would be negative, or close to zero. When the half-amplitude has a positive value, further from zero, it indicates that there is a positive influence from the target face in the previous trial on perception of the target face in the current trial. Trials with response errors exceeding +/- 60 morph steps were considered as errors and were excluded (Liberman et al., 2014).

To test for significance, bootstrapped confidence intervals (CI's) were computed for each condition by randomly resampling each subject's data with replacement 9999 times. A DoG curve was fitted to each resampled dataset generating a distribution of 9999 DoG half-amplitudes based on a population constituted by the data. The boundaries for the 95 % CI's were selected from the distributions of DoG half-amplitudes. 95 % bootstrapped pair-wise contrast CI's between all four conditions were also computed by calculating the average difference between each bootstrapped distribution for each subject and each condition at each resample, generating a distribution of average differences. Individual 95 % bootstrapped CI's for each subject's half-amplitude in each condition and 95 % bootstrapped individual pair-wise contrast CI's were also computed for each subject between all conditions. All statistical analyses were computed in MATLAB (The MathWorks, Natick, MA).

Results

For the RR condition where both target faces in previous and current trials were regular, all subjects displayed significant positive DoG half-amplitudes (a) of serial dependence (Table 2). The mean DoG half-amplitude for this condition was also significantly different from zero, a = 9.73, 95 % CI [7.45, 13.68]. The significant positive DoG half-amplitude shows that there was a perceptual influence from faces in previous trials on perceptions of faces in current trials confirming previous research findings that faces are indeed susceptible to serial dependence (Liberman et al., 2014) (Table 2, Figure 3). Results from the DR condition also showed the expected positive effect of serial dependence with significant DoG half-amplitudes for all subjects and a significant mean DoG half-amplitude, a = 21.67, 95 % CI [18.85, 25.39], indicating that when stimulus reliability for currently viewed target faces were low, there was a stronger positive influence from the more reliable target faces viewed in previous trials (Table 2, Figure 3).

Contrary to what was hypothesized, five subjects displayed positive significant DoG half-amplitudes for the DD condition and one subject displayed a lower, albeit positive, non-significant DoG half-amplitude. The mean DoG half-amplitude for the DD condition also showed a significant positive effect of serial dependence, a = 14.88, 95 % CI [11.4, 19.09], indicating that there was a positive influence from target faces viewed in previous trials on perceptions of target faces viewed in current trials despite both faces being degraded by external visual noise. Individual DoG half-amplitudes for all subjects for each condition and individual CI's are listed in Table 2 and displayed in Figure 3, as well as mean DoG half-amplitudes and CI's for each condition. Figure 4 displays an example of DoG curves for all four conditions from subject 2.

In the RD condition, the individual DoG half-amplitudes were also positive for all subjects. Results for this condition were expected to be low or non-significant since target faces in previous trials for this condition were made unreliable by external visual noise, making regular target faces in current trials the more reliable stimuli. For this condition three subjects displayed the expected low non-significant DoG half-amplitudes, two subjects displayed significant DoG half-amplitudes but still the expected pattern of lower DoG half-amplitudes compared to the RR and DR conditions. One subject displayed a significant DoG half-amplitude that was slightly higher than for the RR and DD conditions but lower compared to the DR condition. The mean DoG half-amplitude was on the border of being non-significant for the RD condition, a = 6.49, 95 % CI [0.27, 9.15], suggesting that serial dependence for this condition was not very strong (Table 2, Figure 3).

Table 2

DoG half-amplitudes and 95 % bootstrapped CI’s for each subject and condition

Condition	RR	DR	RD	DD
Subject	DoG [CI]	DoG [CI]	DoG [CI]	DoG [CI]
1	4.94	13	1.27	13.43
	[0.7, 12.8]*	[5, 20.8]*	[-11.9, 6.6]	[6.5, 21.4]*
2	11.22	16.11	1.27	10.76
	[4.2, 18.3]*	[9.8, 25.5]*	[-16.7, 7.7]	[3, 24.4]*
3	9.67	22.72	8.89	19.05
	[4.6, 14.9]*	[11.5, 27.5]*	[3.3, 14.6]*	[9.4, 27.5]*
4	9.04	19.43	4.93	18.95
	[4.6, 14.9]*	[11.5, 27.5]*	[-17.8, 10.6]	[10.6, 27.6]*
5	13.7	27.85	12.4	20.39
	[7, 26.4]*	[19.7, 35.9]*	[6.4, 19.1]*	[11, 29.3]*
6	9.82	30.88	10.18	6.69
	[4.5, 15.4]*	[24.4, 39.3]*	[3.2, 18.6]*	[-8.9, 15.7]
Mean DoG	9.73	21.67	6.49	14.88
[CI]	[7.45, 13.68]*	[18.85, 25.39]*	[0.27, 9.15]*	[11.4, 19.09]*

Note. Values are DoG half-amplitudes (DoG) and bootstrapped 95 % CI’s for each subject (1-6) for each condition. Mean DoG half-amplitudes and bootstrapped 95 % CI’s for each condition are displayed in the final row. * denotes significant DoG half-amplitudes. Current target face regular – previous target face regular (RR), current target face degraded – previous target face regular (DR), current target face regular – previous target face degraded (RD), current target face degraded – previous target face degraded (DD).

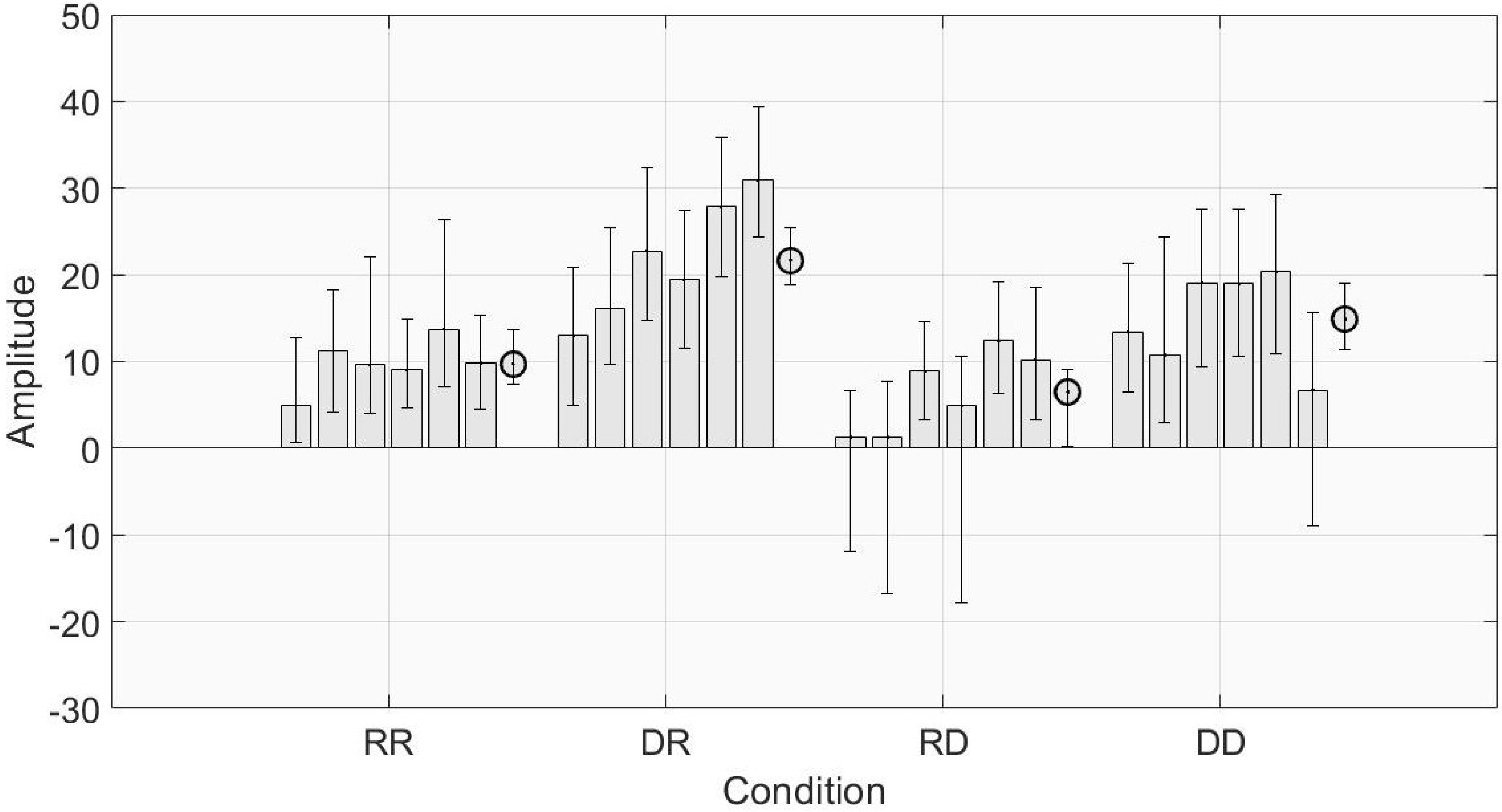

Figure 3. Individual and mean DoG half-amplitudes and 95 % CI's for each condition. Bar graphs display individual DoG half-amplitudes for each subject in each condition. Each bar represents one subject. First bar in each condition = subject 1, second bar = subject 2 etc. Errror bars represents individual 95 % CI's for each DoG half-amplitude. The circles displays mean DoG half-amplitudes for each condition, and the error bars on the circles display 95 % CI's for each mean DoG half-amplitude for each condition. Values are listed in Table 2.

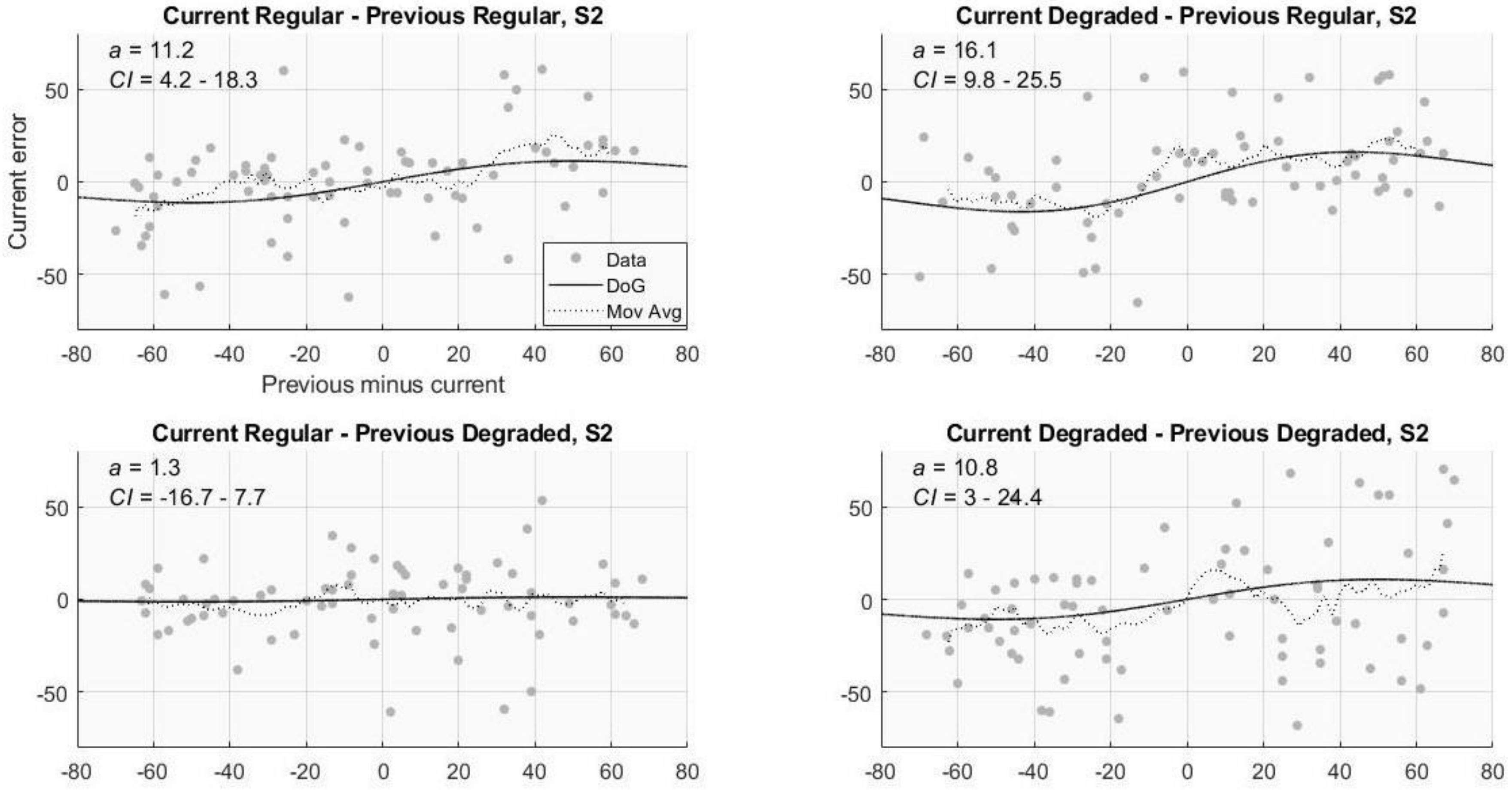

Figure 4. DoG curves for each condition from subject 2. Each data point shows performance on one trial. The horisontal axis is the shortest distance between the current face and the face from the previous trial, and the vertical axis is the shortest distance between the chosen match face and the target face. Dashed line displays the moving average, the derivative-of-Gaussian curve (model fit) is displayed as the solid line. DoG half-amplitudes for each condition is displayed by *a*, along with 95 % CI’s for each condition.

Results from contrast analysis between conditions showed that there was a significantly stronger effect of serial dependence in the DR condition compared to the RD condition, 95% CI [11.67, 22.68], suggesting a significantly higher effect of serial dependence when target faces in previous trials were regular and target faces in current trials were degraded compared to when target faces in previous trials were degraded and target faces in current trials were regular (Table 3). This was the only contrast that was significant for all six subjects further confirming that stimulus reliability did affect serial dependence for faces for these subjects (Table 1; see Appendix). Contrast analysis also showed that on a group level, there was a significantly higher effect of serial dependence in the DR condition compared to the RR condition, 95 % CI [-16.13, -7.11], indicating that serial dependence was significantly stronger when target faces in current trials were degraded and target faces in previous trials were regular compared to when target faces in both previous and current trials were regular (Table 3).

There was also a significantly stronger effect of serial dependence in the DR condition compared to the DD condition, 95 % CI [2.14, 12.31], indicating that the positive influence on current perceptions was stronger when previously viewed target faces were regular and currently viewed target faces were degraded compared to when both previously and currently viewed target faces were degraded. Contrast CI's between all four conditions are listed in Table 3. Significant individual contrast CI's for all subjects between all four conditions are listed in Table 1 in the Appendix.

Contrast analysis further showed that the effect of serial dependence was significantly higher in the DD condition compared to the RD conditon, 95% CI [-16.36, -4.21]. This would indicate that serial dependence was actually stronger when target faces in both trials were degraded by noise compared to when target faces in previous trials were degraded and target faces in current trials were regular. The difference in serial dependence between the RR condition compared to the RD and DD conditions was not significant (Table 3). Average response time (RT) across all trials for all subjects was 11017 ms (*SD* = 3465 ms). Individual average response times for all subjects across all trials are listed in Table 2 in the Appendix.

Table 3
95 % Bootstrapped contrast CI's between all conditions.

Condition	Contrast CI's
RR – DR	[-16.13, -7.11]*
RR – RD	[-0.03, 12.20]
RR – DD	[-9.42, 0.17]
DR – RD	[11.67, 22.68]*
DR – DD	[2.14, 12.31]*
RD – DD	[-16.36, -4.21]*

Note. Bootstrapped 95 % contrast CI's between all conditions. * denotes significant contrasts. Current target face regular – previous target face degraded (RR), current target face degraded – previous target face regular (DR), current target face regular – previous target face degraded (RD), current target face degraded – previous target face degraded (DD).

Discussion

Serial dependence has been explained as an adaptive mechanism operating to integrate previous visual information with current visual information in order to create perceptual stability in an environment consistent of disturbances due to changes and different sources of visual noise (Kiyonaga et al., 2017; Liberman et al., 2014). In the present study, the role of stimulus reliability in serial dependence for faces was investigated in one experiment by presenting degraded and regular target faces in four different conditions. The RR condition, used as baseline in the present study, confirmed the presence of serial dependence for faces (this serial dependence for faces without external noise is thoroughly explained in Liberman et al. (2014) and will not be discussed further here). The results from the present study also supported the main hypothesis that serial dependence for faces is affected by stimulus reliability. When unreliable facial stimuli were presented in a sequence along with reliable facial stimuli, there was a positive influence from the more reliable stimuli on most subjects current perceptions. This could further confirm that serial dependence does operate as a noise reduction mechanism in the manner of a perceptual information integrator, where predictions regarding the current state of the world are positively influenced by the more reliable information available (Cicchini et al., 2014, Cicchini et al., 2018; Kiyonaga et al., 2017). Surprisingly though, results from the DD condition threw a bit of a curveball, suggesting that serial dependence still ocurred when both target faces in previous and current trials were unreliable. This was an unexpected effect that could indicate that the variation in serial dependence for faces caused by stimulus reliability is not due to the inability to encode a face, but rather a perceptual choice.

For the DR and RD conditions, the results in this study were in line with previous findings that serial dependence is affected by stimulus reliability (Cicchini et al., 2014; Cicchini et al., 2018). When target faces in previous trials were degraded and target faces in current trials were regular, most subjects showed a smaller effect of serial dependence and the mean DoG half-amplitude for the RD condition was lower and on the border of being non-significant. When the condition was reversed, and target faces in current trials were degraded, all subjects displayed a significant positive influence from the regular target faces presented in previous trials on their current perceptions. The positive effect of serial dependence for the DR condition was also significantly stronger compared to the RD condition.

Within the accounts of Bayesian cognitive science, the human brain is suggested to act as an ideal observer which relies on posterior probability distributions in perceptual desicion making. Counterintuitive as it may sound, the word ideal does not imply that this theoretical observer would produce perceptual outcomes which mirrors the truth about the current environment. What it does imply is that the ideal observer would integrate visual information from variable sources in a statistically optimal manner, where the outcome would be a best guess about the current state of the world. Whether this guess is more reliant on prior information or current information would be determined by stimulus reliability, hence, perceptual information higher in reliability would be highly influential on how the current state of the world is perceived (Kersten et al., 2004; Yuille & Kersten, 2006). This means that this ideal observer would be very susceptible to produce illusory percepts and could very well produce these serial dependence effects present in the RD and DR conditions. When faced with visual uncertainty, the ideal observer will use the integration process in an attempt to disregard visual noise, and in certain situations, like in the DR condition, illusion will prevail.

Visual uncertainty can be interpreted as how much confidence one has in what one sees. Researchers using functional magnetic resonance imaging (fMRI) suggests that visual confidence can be constituted as internal probability distributions which reflects sensory uncertainty in visual cortex. The probability that a specific stimulus is present is represented by the current neuronal activity induced by a visual percept. Knowledge drawn from these internal probability distributions is considered to be what individuals base their perceptual decisions on (Barthelmé & Mamassian, 2010; van Bergen et al., 2015). Explicit reports for visual confidence would thus be a summary estimated from these internal probability distributions (Meyniel et al., 2015). In line with these suggestions, Suaréz-Pinilla et al. (2018) found that when subjects explicitly reported high confidence ratings for stimuli viewed in current trials, there was very little or no positive serial dependence effects from stimuli viewed in previous trials. The authors interpreted these confidence ratings as internal visual uncertainty translated into explicitly expressed confidence. Although, subjects in the present study were not asked to provide explicit confidence ratings, the same pattern of serial dependence effects for stimulus uncertainty as discovered by Suaréz-Pinilla et al. (2018) was also found here.

It might have been plausible to assume that the smaller serial dependence effect in the RD condition could possibly be explained as a product of stimulus dissimilarity. Object similarity has been found to be crucial for serial dependence to occur, and objects too dissimilar in appearance or contrast has been shown to produce a negative after-effect rather than a positive dependence (Liberman et al., 2016). Target faces could have been perceived as very different when they were viewed through noise in previous trials and as regular in current trials. However, object dissimilarity does not explain the high positive serial dependence for the DR condition where stimuli positions were reversed.

Considering subjects in the present study did seem to be positively influenced by the regular target faces considered lower in uncertainty in the DR and RD conditions, it is tempting to suggest that these subjects did act as ideal observers, implicitly basing their perceptual decisions on internal sensory uncertainty where stimuli lower in uncertainty were allowed to positively influence their current perceptions. This would also be consistent with the suggestion that serial dependence as a predictive process operates to save cortical resources and thus makes an attempt to disregard the noise and rely on stimuli that takes less effort to encode (Manassi et al., 2018). That noisy sensory representations can benefit from information integration from different sources is supported by literature regarding regression to the mean and multisensory integration (Alais & Burr, 2004; Ernst & Banks, 2002; Kersten et al., 2004). The impact of stimulus reliability in serial dependence for orientation, as well as perception as a predictive process, has also been successfully explained by cognitive modellers using Bayesian ideal observer models (Cicchini et al., 2014; Cicchini et al., 2018; Schmack, Weilnhammer, Heinzie, Stephan & Sterzer, 2016).

Intuitively one might assume that noise would decrease a viewer's ability to attend to and encode a face. Previous literature has indeed suggested that external visual noise does have a negative impact on face perception (Chen et al., 2015; Corrow et al., 2018; Duchaine & Nakayama, 2006; Macke & Wickmann, 2010). Judging only from the results from the DR and RD condition, a viable conclusion could have been that the positive influence from the more reliable regular facial stimuli was caused by the inability to properly encode the degraded target faces. However, results from the DD condition indicates that drawing such a conclusion might just lead us down the wrong path. These results unexpectedly indicated that for all but one subject, there was a significant positive effect of serial dependence when both target faces in previous trials and current trials were degraded by noise.

The level of Gaussian noise used in the present study was 0.3, which was expected to reduce the ability for subjects to rely on proper face processing mechanisms. Some research suggests that external noise could under some circumstances actually be of aid in increasing viewers detection performance rather than decreasing it, a phenomenon termed *stochastic resonance* (SR). Adding visual noise has been found to strengthen the detection of weak visual signals, as well as increasing phase synchronization of EEG signals from extensively distant brain areas, possibly leading to a prominent neural synchronization which could enhance a viewer's detection performance (Kitajo et al., 2007; McDonnel & Abbot, 2009). Perceptual learning has also been indicated to lead to SR, where neurons learn to reduce their responses to irrelevant noise and thus more effectively infuse the relevant signals from a visual stimulus. This enhancement in detection performance through perceptual learning in the presence of external visual noise has been shown to occur in visual pattern recognition for both face identification and texture discrimination (Hurlbert, 2000).

Some research in face perception also indicates that visually degraded faces can still be encoded, and identified in later recognition tasks despite individuals not having visual access to the whole face image. If making the assumption that holistic processing is nedeed for face perception to occur, this could indicate that holistic processing is not as sensitive to external visual noise as some research would suggest (Royer, Blais, Gosselin, Duncan & Fiset, 2015). Since serial dependence is reliant on the ability to attend to and encode visual stimuli, the results from the present study could indicate that most of the subjects were able to properly encode the faces in the DD condition despite the present level of external visual noise. However, Paras & Webster (2013) found that just seeing dark spots in noisy images can give the impression of a face-like percept. These face-like percepts did not elicit responses from the N170 (i.e., event related potential (ERP), known to respond to faces), nor did they produce the fixation patterns that would be expected from images of faces. This could suggest that despite not all aspects of face processing mechanisms being involved, the holistic processing needed for face perception can still be partially invoked from very simple face-like percepts (Paras & Webster, 2013). The point here is, one cannot be absolutely certain that faces in the DD condition were encoded on the level of identity, nor can one be certain that holistic processing is not very sensitive to noise and possibly would have been involved on a more representational level (Royer et al., 2015). The only assumption that can be made is that serial dependence for faces might still occur in situations of stimulus uncertainty when both previous and current facial stimuli are unreliable due to external visual noise.

Since external visual noise is expected to enhance overall stimulus uncertainty (Bitzer & Kiebel, 2015; Hulme & Zeki, 2007), this opens up to further questioning why the degraded target faces in the DD condition seemed to elicit a higher positive influence on most subjects perceptions compared to the degraded target faces in the DR and RD condition. According to a substantial amount of evidence, conscious perception of a stimulus is not possible without attention, and research states that serial dependence cannot occur without the possibility of encoding and attending to a stimulus (Dehaene, Changeux, Naccache, Sackur & Sergent, 2006; Kiyonaga et al., 2017). According to the *perceptual template model*, attention can either act as an amplifier for a perceptual signal in the absence of noise, or as a filter, strengthening the relevant perceptual signal in noisy conditions. Attention as a noise-filtering operator is only thought to occur when the level of external visual noise is quite high (Pratte, Ling, Swisher & Tong, 2013).

Attention has also been found to alter the appearance of stimuli. When stimuli is briefly attended to, subjects report perceiving low-contrast stimuli higher in contrast than they actually are compared to high-contrast stimuli, suggesting that attention can alter the strength of a stimulus by enhancing its contrast (Carrasco, Ling & Read, 2004). Research on macaque monkeys has shown that neurons responding to attention has a lower firing rate for high-contrast stimuli compared to low-contrast stimuli which could further support the influence of attention on stimulus contrast effects (Reynolds, Pasternak & Desimone, 2000). Induced stimulus strength by automatically initiated bottom-up attentional mechanisms and top-down attentional amplification combined can sometimes be enough to carry a stimulus across the threshold for conscious perception (Anderson & Phelps, 2001; Dehaene et al., 2006).

Heightened attentional resources and lower perceptual thresholds could possibly explain the significant positive effect in the DD condition which was also significantly stronger compared to the RD condition. Some research suggests that individuals implicitly adjust their perceptual decisions according to internal levels of attention (Denison, Adler, Carrasco & Ji Ma, 2018). There might not be a need for high levels of attention in the DR and RD conditions where there were reliable visual information available. The relationship between perceived stimulus strength and attention could also explain why the positive serial dependence in the DD condition, for all but two subjects, reached an effect slightly higher than for the RR condition. This could suggest that the role of attention in serial dependence might not only apply to attention between stimuli, but also on the level of attentional resources activated for a specific stimulus.

It would also be plausible to assume that in situations where there is a perceptual choice between reliable and unreliable stimuli, the choice is to allow a higher positive influence from the more reliable stimuli and that this choice is not made based on the inability to encode stimuli, but rather an attempt to disregard the noise and create stable visual percepts, possibly due to internal levels of attention. Again, this could also suggest that serial dependence as a mechanism operates to reduce neural resources by automatically trying to reject noisy visual information, but only when there is a possibility to do so. Whether attentional resources in the DD condition could have induced proper face processing or not is still not possible to say, so refraining from speculation, one can only assume that these degraded target faces were on some level encoded given that serial dependence would not be possible without being able to consciously attend to and encode stimuli (Kiyonaga et al., 2017). Attention as a noise-filtering mechanism from an ideal observer point of view would be consistent with these results, but explaining how such processes would work is beyond the scope of the present study (see, e.g., Denison et al., 2018; Geisler, 2011).

One difference between the present study and Liberman et al. (2014) was that here, no responses were excluded due to response time. According to some previous research, serial dependence is affected by inter-trial time and can only occur within a timeframe of up to 15 s back in time (Kiyonaga et al., 2017). This would mean that including response times exceeding 15 s should have produced smaller effects of serial dependence and DoG curves more close to flat lines. The conclusion that serial dependence only occurs within a 15 s continuity field has been drawn mostly from studies using Gabor gratings as visual stimuli. However, Suaréz-Pinilla et al. (2018) did find that inter-trial time did not affect serial dependence for visual variance. They found that the positive perceptual influence could be traced to stimuli seen up to four trials back, suggesting that inter-trial time was not of importance. Research states that the brain can make predictions locally based on a preceeding stimulus as well as by accumulating evidence over time, where evidence accumulation for visual information can take the shape of ensemble representations even when the visual input is not complete (Darriba & Waszak, 2018; Haberman & Ulrich, 2019; Todorovic & de Lange, 2012).

Research regarding face perception and probabilistic theories of visual perception would support the notion that individuals might process faces by using statistical regularities (i.e., pattern types, spatial organization) that will include some estimation of variability (Hayward, Crookes, Chu, Favelle & Rhodes, 2016; Yuille & Kersten, 2006). Customed by evolution, faces are uniquely high in variability. The spatial relations between the eyes, nose, and mouth are specifically variable between individuals. Faces also have low inter-trait correlations and large variances in spatial distances between forehead, chin and pupils, making them highly complex visual stimuli that puts a higher strain on our perceptual abilities (Sheehan & Nachman, 2014). Adding noise to a face image would also heighten visual variability further (Hulme & Zeki, 2007). Making inferences from artificial laboratory stimuli has been questioned since research show that neuronal responses for gratings compared to natural stimuli differ from one another (Mante, Frazor, Bonin, Geisler, & Carandini, 2005). Using artificial stimuli to understand visual processes is according to Yuille and Kersten (2006) like ”trying to evaluate the performance of a soldier in battle from his ability at playing with a water pistol” (p. 1). Even though inter-trial time was not controlled for in this study, not excluding responses due to time could modestly indicate that inter-trial time was not of importance here and that there is a possibility that serial dependence could operate differently depending on the experimental stimuli used in different studies.

It should be mentioned that there were some individual differences between subjects in the RD and DD conditions in the present study. One subject did show a stronger perceptual influence from the previous trial in the RD condition and one subject showed a lower effect of serial dependence in the DD condition. Some research indicates that SR is dependent on the amount of internal noise (i.e., internal uncertainty) which could differ between individuals. For individuals with low internal noise there can be a benefit for visual perception when external noise is added (Aihara, Kitajo, Nozaki & Yamamoto, 2008). Some evidence also indicates that there could be individual differences in the ability to recognize faces even for healthy subjects (Royer et al., 2015). There is also a possibility that subjects in the present study used different attentional strategies (Reynolds & Heeger, 2009). These are all factors that could have an impact on the results and possibly explain why there was a difference in serial dependence between subjects in these two conditions.

*Limitations, further research and conclusion*s

One obvious limitation in the present study is the small amount of data collected from each subject. There is a possibility that more data could have affected the results and suggested different conclusions from those made here. Even though the replication of Liberman et al.’s (2014) experiment 1 (i.e., RR condition) did produce a similar result to the original experiment, I would advise that all conclusions drawn in this study should be considered as modest interpretations of the results. It will be up to future research to investigate serial dependence for faces in this context further with larger amounts of data. Future research could also benefit from investigating serial dependence for faces by varying the level of visual noise, combined with explicit confidence reports, one might get a notion of how reliable faces are considered to be when seen through different levels of visual noise and also determine the noise thresholds for stimulus reliability in serial dependence for faces. Varying levels of visual noise and using brain imaging techniques could also be a possibility for investigating the role of how different levels of attention could affect the process of serial dependence for faces. Taken together, this could give further insight regarding the relationship between attention, noise-filtering and serial dependence. In addition, cognitive models like the Bayesian ideal observer model, used to explain stimulus reliability for serial dependence in orientation, could be adjusted to fit data from the above suggested further research and from the present study by noise manipulation (Cicchini et al., 2014; Cicchini et al., 2018), as well as signal detection models which could also be used as an alternative in this context (Verghese, 2001).

Concluding remarks here would be that the results from the present study do suggest that serial dependence for faces is affected by stimulus reliability and would further support previous findings suggesting that serial dependence is an information integrator possibly in the sense of an ideal observer. The results would further suggest that serial dependence does not try to disregard noisy visual inputs due to encoding disabilities, but rather seems to choose to do so when there is a possibility of allowing reliable stimuli to have a positive influence on current perception. Whether this involves perceptual learning, attentional resources/noise-filtering, face processing mechanisms, or that the level of noise here just happened to be the exact level of ”good” noise that would induce SR in the DD condition, is yet to be explained. Previous research investigating visual perception as a predictive process combined with the results from the present study could suggest that seeing should not always be believing. When the very sinister character Top Dollar in the cult movie The Crow (1994) hoarsely stated that ”all the power in the world resides in the eyes, fella”, he might not have been too far from the truth. Judging from the results presented here, the visual system might not have all the power in the world, but it might just own the power of deception.

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Appendix

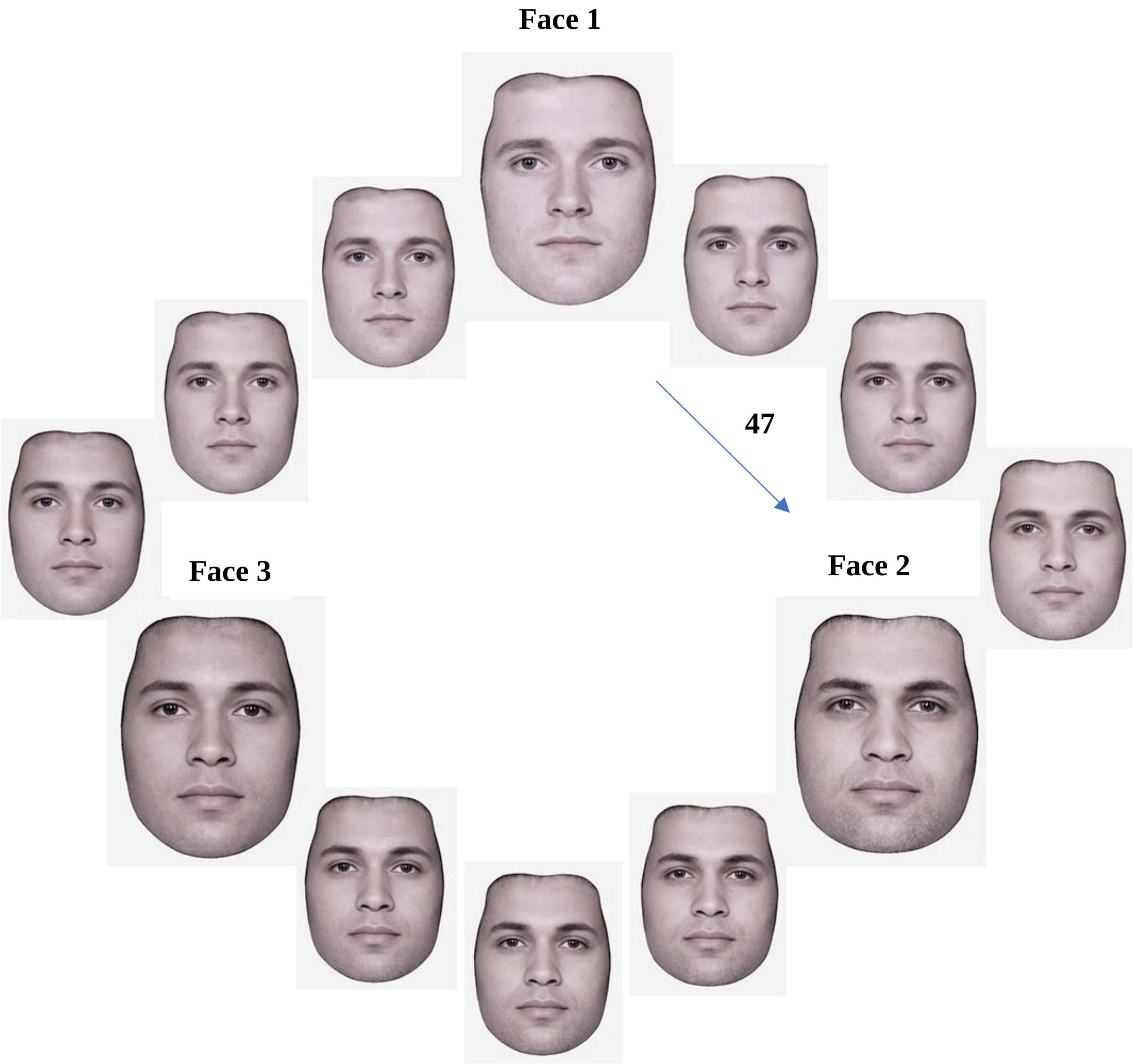

Figure 1. Face morph continuum. Morphed continuum containing the three original faces (i.e., face 1, 2, and 3) and example faces from the 142 face morph continuum. Arrow shows the direction of the morphed continuum. There were 47 morphed faces between each original face.

Table 1

Significant individual 95 % bootstrapped contrast CI's for all subjects between all conditions

			Contrast CI's			
Subject	1	2	3	4	5	6
Condition						
DR – RR	—	—	—	[0.2, 19.04]	[0.47, 25.3]	[11.73, 30.99]
RR – RD	—	[0.33, 29.53]	—	—	—	—
RR – DD	—	—	—	—	—	—
DR – RD	[2.05, 27.53]	[6.18, 35.39]	[3.28, 25.26]	[3.98, 25.92]	[5.36, 25.43]	[10.16, 32.43]
DR – DD	—	—	—	—	—	[12.9, 40.89]
RD – DD	[-29.3, -4.03]	—	—	[-25.89, -4.49]	—	—

Note. Values are significant 95 % bootstrapped contrast CI's for all subjects between all conditions. Current target face regular – previous target face regular (RR), current target face degraded – previous target face regular (DR), current target face regular – previous target face degraded (RD), current target face degraded – previous target face degraded (DD).

Table 2

Individual average response times and standard deviations

Subject	Average RT	*SD*
1	8151	6016
2	8666	6961
3	7449	4984
4	12480	10144
5	13166	8925
6	16195	10037

Note. Individual average response times (RT) and standard deviations (*SD*) in milliseconds for all subjects across all trials.