Additional Analyses for Supplemental Online Material to Accompany Kok et al.'s "How Positive Emotions Build Physical Health: Perceived Positive Social Connections Account for the Upward Spiral Between Positive Emotions and Vagal Tone"

These analyses include:

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Preliminary Analyses

Preliminary analyses described in this section confirmed that a) it was appropriate to model positive emotions and social connections as latent curves, b) the experimental intervention influenced positive emotions, social connections, and vagal tone as hypothesized, and c) initial levels of vagal tone interacted with experimental condition to predict steeper increases in positive emotions and social connections over the course of the study.

Two separate latent curve models, one for positive emotions and one for social connections, were constructed to test both constructs individually. In these models, weekly averages for either positive emotions or social connections over the course of the study loaded on an intercept factor, representing scores on the construct at baseline, and a slope factor, representing the slope of change in the construct over the course of the study. All intercept factor loadings were fixed to 1, and slope factor loadings were fixed to week in the study, beginning with 0 for the baseline week. Experimental condition, baseline vagal tone, and their interaction predicted both intercept and slope of change in positive emotions or social connections, respectively, over the course of the study. The paths from experimental condition, baseline vagal tone, and their interaction to the intercept factors were not expected to be significant, but were included to confirm this and for proper scaling of the paths to the slope factor. These and all other structural equation models described in this study were estimated in mPlus version 6.1, using maximum likelihood estimation and all available data.

Results from the latent curve model for positive emotions indicated that the model fit the data (RMSEA = 0.06, 90% CI = 0.00-0.10, CFI = 0.98) and that the interaction of experimental condition and baseline vagal tone significantly predicted slope of change in positive emotions over the course of the study ($b = 0.04$, $z = 2.38$, $p = 0.02$). Experimental condition alone also significantly predicted slope of change in positive emotions ($b = 0.05$, $z = 3.25$, $p = 0.001$), whereas baseline vagal tone did not ($b = -0.01$, $z = -1.00$, $p = 0.32$), however this is likely to be because baseline vagal tone was mean-centered whereas the original binary coding for experimental condition was retained. As expected, neither experimental condition ($b = -0.02$, $z = -0.10$, $p = 0.93$), baseline vagal tone ($b = 0.06$, $z = 0.49$, $p = 0.63$), nor their interaction ($b = 0.13$, $z = 0.60$, $p = 0.55$) significantly predicted baseline positive emotions scores.

Results from the latent curve model for social connections indicated that this model also fit (RMSEA = 0.068, CFI = 0.976). As with positive emotions, the interaction of experimental condition and baseline vagal tone significantly predicted slope of change in social connections ($b = 0.07$, $z = 2.66$, $p = 0.008$). Experimental condition alone also predicted slope of change on social connections whereas baseline vagal tone alone did not, however, as described above, this difference is likely to an artifact of mean-centering baseline vagal tone. Neither experimental condition ($b = -0.31$, $z = -1.09$, $p = 0.28$), baseline vagal tone ($b = 0.11$, $z = 0.62$, $p = 0.54$), nor their interaction (b = -0.15, z = -0.48, p = 0.63) significantly predicted baseline social connections scores.

Lastly, a t-test examined whether experimental condition predicted change in vagal tone over the course of the study. We hypothesized that experimental condition would predict change in vagal tone, rather than simply raw vagal tone scores, thus for the post-treatment vagal tone assessment, we used the standardized residual of post-treatment vagal tone when it is regressed on baseline vagal tone. This partials out the impact of baseline vagal tone and allowed us to focus exclusively on change in vagal tone over the course of the study. Results from the t-test indicated that experimental condition predicted an increase in vagal tone over the course of the study (t = -1.93, df = 36 with unequal variances, *two-tailed* p = 0.06, *one-tailed* p = 0.03).

Non-Hypothesized Paths

Experimental condition, baseline vagal tone, and their interaction predicted baseline positive emotions (paths *a* – *c*) and slope of change in positive emotions over the course of the study (paths *d* – *f*). Per Hypothesis 1, we expect that LKM participants to report more positive emotions over time than control participants, but that this effect would be even greater for those LKM participants who began the study with higher levels of vagal tone. Path *e*, examining the joint impact of baseline vagal tone and positive emotions training on change in positive emotions, tested Hypothesis 1. We tested Hypothesis 2 with a direct effect from slope of change in positive emotions to slope of change in social connections (path *h*). A direct effect from the intercept of positive emotions to the intercept of social connections reflected the relationship that we expected between these constructs at baseline (path *g*). The direct effect from slope of change in social connections to change in vagal tone (path *k*) tested Hypothesis 3. Thus, the critical paths in our upward spiral model linking vagal tone, positive emotions, and social connections examined the impact of the interaction of experimental condition and baseline vagal tone on slope of change in positive emotions (path *e*, Hypothesis 1), the impact of slope of change in positive emotions on slope of change in social connections (path *h*, Hypothesis 2), and the impact of slope of change in social connections on change in vagal tone (path *k*, Hypothesis 3).

The model also included direct effects from the intercepts of positive emotions (path not pictured) and social connections (path *j*) to change in vagal tone. These paths were not expected to be significant, but were included to rule out the possibility that it is baseline levels of these constructs, rather than change in them, that predicts change in vagal tone.

Estimates for paths in the model unrelated to our hypotheses were also consistent with the literature. Baseline positive emotions significantly predicted baseline social connections (path *g*; $b = 1.11$, $z = 7.23$, $p < 0.001$), indicating that, unsurprisingly, baseline levels of these constructs were strongly associated with each other. In addition, neither baseline positive emotions ($b = 0.07$, $z = 0.24$, $p = 0.81$) nor baseline social connections (path *p*; $b = -0.22$, $z = -1.20$, $p = 0.23$) significantly predicted change in vagal tone over the course of the study, indicating that it was not simply those who were initially high on these constructs who exhibited increases in vagal tone.

Intent-to-Treat Analyses

LKM was employed in this study as an experimental manipulation, rather than as a “treatment.” Thus, we feel it is appropriate to remove from the analyses those participants who did not meaningfully participate in the study, or who violated initial exclusion criteria. Nonetheless, we recognize that this study also has relevance for better understanding the benefits of LKM, as a clinical intervention. In this spirit, we conducted intent-to-treat analyses that incorporated all participants who were randomized to experimental condition and provided data for at least one assessment (n = 70). These analyses yielded results very similar to those we report above. Overall model fit was acceptable (RMSEA = 0.068; 90% CI = 0.045-0.088, CFI = 0.96) and the pattern of significant paths remained the same. Of most importance, the paths from the interaction of experimental condition and baseline vagal tone to slope of change in positive emotions (path *e*; b = 0.04, z = 2.68, p = 0.007), from slope of change in positive emotions to slope of change in social connections (path *h*: b = 1.06, z = 4.09, p < 0.001), and from slope of change in social connections to change in vagal tone (path *k*; b = 4.31, z = 2.11, p = 0.04) were all significant.

Respiratory Sinus Arrhythmia Analyses

We also tested the model with an alternate index for vagal tone, RSA, instead of HF HRV. Respiratory sinus arrthymia (RSA) is a non-invasive measure of cardiac vagal control characterized by increases in heart rate with inspiration and decreases in heart rate with expiration (Porges, 2007; for more information on heart rate variability assessment, see Bernston et. al, 1997). Respiration data was collected with pneumatic bellows, placed around the participant's chest with continuous recordings made at a sampling rate of 1000 Hz. RSA was calculated off-line, based on changes in heart rate associated with respiration. We used a modified Grossman peak-to-valley method (Grossman, 1983) with data resampled every 125 milliseconds, excluding areas where no peaks or valleys could be identified. The analyses based on RSA were largely similar to those based on HR-HRV, although some differences emerged. Whereas the interaction of baseline HF HRV and experimental condition significantly predicted slope of change in positive emotions (described above), the interaction of baseline RSA and experimental condition did not (b = 0.02, z = 1.21, p = 0.23). Removing the non-significant interaction term from the model revealed that experimental condition significantly predicted slope of change in positive emotions (b = 0.05, z = 3.18, p = 0.001), whereas baseline RSA (b = 0.01, z = 1.31, p = 0.19) did not. All other aspects of the model were consistent with results when HF HRV represented vagal tone, including the significant paths from change in positive emotions to change in social connections, and from change in social connections to change in RSA-assessed vagal tone. Overall model fit was worse than for the HF HRV model (RMSEA = 0.090, 90% CI = 0.069-0.110, CFI = 0.94).

Alternative Models

In a last set of analyses, we explored a variety of competing but un-hypothesized explanations for the data. These included the possible role of negative emotions in driving the change in the model (alternative explanation #1), the specific placement of positive emotions, social connections, and vagal tone in the model (alternative explanations #2 and #3), the possibility that positive emotions is not a necessary mediator of experimental condition and vagal tone's influence on social connections (alternative explanation #4), and the possibility that social connection is not a necessary mediator of positive emotion's influence on change in vagal tone (alternative explanation #5).

1. Could the findings be explained by change in negative, rather than positive, emotions? Most participants endorsed relatively low levels of negative emotions, creating positively skewed distributions for all weekly negative emotion variables. To address positive skew, these variables were transformed by taking their natural log. The model estimated was then identical to the one for positive emotions.

The negative emotions model produced an error message indicating that the standard errors for some parameters may not be trustworthy, and suggesting that the problem involved the impact of the interaction of experimental condition and baseline vagal tone on slope of change in negative emotions. (Mean-centering experimental condition, to remove any possible multicollinearity with the interaction term, did not eliminate this problem.) Removing the interaction term and associated paths (paths *b* and *e*) effectively resolved these errors. The resulting model produced an RMSEA of 0.078 (90% CI = 0.055-0.099, CFI = 0.95), indicating acceptable model fit. Experimental condition significantly influenced change in negative emotions (path *d*; $b = -0.02$, $z = -2.29$, $p = 0.02$), such that participants randomly assigned to the LKM group reported steeper declines in negative emotions over the course of the study. Baseline vagal tone predicted neither baseline negative emotions (path *c*; $b = -0.03$, $z = -0.85$, $p = 0.40$), nor change in negative emotions over the course of the study (path *f*; $b = 0.001$, $z = 0.30$, $p = 0.77$). Change in negative emotions exerted a marginally significant impact on change in social connections (path *h*; $b = -0.98$, $z = -1.71$, $p = 0.09$), indicating that greater decreases in negative emotions were marginally significantly associated with greater increases in social connections. Greater change in social connections predicted greater change in vagal tone (path *k*; $b = 5.21$, $z = 2.06$, $p = 0.04$), however this relationship did not reflect mediation of the relationship between negative emotions slope and change in vagal tone by social connections. When we fixed the path from social connections slope to change in vagal tone (path *h*) to zero, and added a direct effect from negative emotions slope to change in vagal tone, the direct effect between slope of change in negative emotions and change in vagal tone was not significant ($b = -2.54$, $z = -0.42$, $p = 0.67$). These data suggest that the findings reported for positive emotions cannot be explained by a reduction in negative emotions.

2. Are positive emotions and social connections interchangeable? Another possibility is that positive emotions and social connections are so closely linked as to be interchangeable. We tested this possibility by transposing positive emotions and social connections in the model, such that experimental condition, baseline vagal tone (baseline HF HRV), and their interaction predicted slope of change in social connections, which in turn predicted slope of change in positive emotions. Positive emotions then predicted change in vagal tone. As with negative emotions, this model generated an error indicating that the interaction term for baseline vagal tone and experimental condition created problems with model identification. (Mean-centering experimental condition did not eliminate this problem.) Removing the interaction term and associated paths (paths *b* and *e*) effectively resolved these errors. The resulting model indicated that baseline vagal tone did not predict change in social connections (b = 0.02, z = 1.51, p = 0.13), whereas experimental condition did (b = 0.07, z = 3.08, p = 0.002). Change in social connections did in turn predict change in positive emotions (b = 0.54, z = 4.18, p < 0.001), but change in positive emotions did not predict change in vagal tone (b = 3.67, z = 1.22, p = 0.22). Thus, when positive emotions and social connections were transposed, critical paths were no longer significant, thereby failing to fully model the relationships among baseline vagal tone, change in positive emotions, change in social connections, and change in vagal tone. Overall model fit was worse than for our hypothesized model (RMSEA = 0.086, 90% CI = 0.065-0.106, CFI = 0.95).

3. Does change in vagal tone drive change in the other constructs? A third possibility is that the experimental intervention directly impacted vagal tone, and it was change in vagal tone that in turn impacted positive emotions and social connections. To test this, we constructed a model in which experimental condition alone influenced change in vagal tone (HR HRV), which in turn influenced slope of change in positive emotions, and which then influenced slope of change in social connections. We retained all other aspects of our original model, including the path from the positive emotions intercept to the social connections intercept (path *g*) and the residual covariances for the positive emotions and social connections weekly variables. Model fit was marginal (RMSEA = 0.091, CFI = 0.94). Experimental condition did significantly and directly predict change in vagal tone ($b = 0.53$, $z = 1.97$, $p = 0.05$), however change in vagal tone did not significantly predict change in positive emotions ($b = 0.01$, $z = 1.11$, $p = 0.27$). Thus, this model did not support this alternative explanation for the relationships among the constructs. Change in positive emotions did predict change in social connections ($b = 0.95$, $z = 3.87$, $p < 0.001$), however.

4. Are positive emotions a necessary mediator between experimental condition and vagal tone, and social connections? To explore the possibility that positive emotions are not a necessary mediator, we first added three additional paths to the model: direct effects from experimental condition, baseline vagal tone, and their interaction to social connections slope of change. These paths permitted experimental condition and baseline vagal tone to influence social connections slope directly, rather than via positive emotions. This model produced a χ^2 of 302.8 ($df = 217$, RMSEA = 0.078, CFI = 0.95, AIC = 2071.9), indicating acceptable model fit. All previously significant paths remained significant, yet each of the three new paths was non-significant.

We then fixed the critical path by which positive emotions slope influenced social connections slope (path *h*) to zero, preventing change in positive emotions from mediating the impact of experimental condition, vagal tone, and their interaction on change in social connections. This model produced a χ^2 of 306.3 ($df = 218$, RMSEA = 0.079, CFI = 0.95, AIC = 2073.4), indicated acceptable model fit. When path *h* was fixed to zero, the direct effect from the interaction term to social connections slope become significant ($b = 0.056$, $z = 2.46$, $p = 0.01$). All previously significantly paths remained significant. Nonetheless, fixing path *h* at zero marginally significantly worsened model fit (χ^2 = 3.5, *df* = 1, *p* = 0.06), providing support for the importance of change in positive emotions as a mediator in the model.

5. Is social connections slope of change a necessary mediator between positive emotions slope of change and change in vagal tone? To explore the importance of social connections as a mediator between positive emotions and vagal tone, we first returned to our original, hypothesized model and added one additional path: a non-significant direct effect from positive emotions slope to change in vagal tone (*b* = -4.84, *z* = -0.80, *p* = 0.42). This model produced a χ^2 of 305.9 (*df* = 219, RMSEA = 0.078, CFI = 0.95, AIC = 2070.9).

We then fixed the path from social connections slope to change in vagal tone (path *k*) to zero, preventing social connections slope from mediating the impact of positive emotions slope on change in vagal tone. This model produced a χ^2 of 309.7 (*df* = 220, RMSEA = 0.079, CFI = 0.95, AIC = 2072.7). This represented a significant worsening in model fit (χ^2 = 3.8, *df* = 1, *p* = 0.05), which provides support for the importance of change in social connections as a mediator in the model. Interestingly, the path from positive emotions slope to change in vagal tone remained non-significant (*b* = 4.41, *z* = 1.45, *p* = 0.15), even when path *k* was fixed to zero.

References for the Supplementary Materials

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